

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**ADAPTIVE ONLINE PARAMETER OPTIMIZATION OF
VEHICLE CONTROL MODULE TO SATISFY VARYING
PERFORMANCE AND DRIVABILITY METRICS**

ÖZER ULUCAY

**A THESIS OF DOCTORATE
MECHANICAL ENGINEERING DEPARTMENT**

ADVISOR: PROF. DR. SELİM SİVRİOĞLU

MARCH 2024

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T.C.
GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

PERFORMANS VE SÜRÜLEBİLİRLİK ÖLÇÜTLERİNİ SAĞLAMAK İÇİN
MOTOR KONTROL ÜNİTESİNİN UYARLANABİLİR ÇEVİRİMİÇİ
PARAMETRE OPTİMİZASYONU

ÖZER ULUCAY

DOKTORA TEZİ
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*To my lovely family;
my parents, my wife Tuğba
and my children Meryem &
Ahmed Akif.*

ABSTRACT

In automotive control modules, lookup tables are used for system control and parameter optimization is necessary since there are trade-offs and optimization methods are needed to be applied for optimum performance. However, it is very time-consuming step in development phase and has become necessary after the production. The initial performance and drivability of vehicles are adversely affected depending on the distance and conditions of use; however, current engine control unit software structure does not allow tracking changes in powertrain system control. This thesis proposes a self-tuning algorithm that yields optimized performance and drivability throughout the life span of the vehicle over against changes due to mechanical wear and aging. Besides, for customer satisfaction both drivability and performance attributes must be considered and there are trade-offs between them. Optimization takes time and requires expertise for drivability and performance attributes since objective metrics are not available and generally subjective assessment is used for signoff. Therefore, another challenging aspect of this study is determination of a combined cost function for performance and drivability attributes. Tip-in maneuver is selected, and design of experiments is prepared and performed with small passenger and light commercial vehicles in controlled environment in a test track. Response surface methodology is adopted to correlate objective data and subjective assessments, and objective criteria functions are obtained. For combined objective evaluation, overall tip-in rating is also formulated from criteria ratings using correction factors for each rating and weight factors of each criterion. Golden section algorithm is used for optimization. The proposed methodology is applied and validated in a prototype vehicle and results are presented. In addition, vehicle and elastic driveline plant model is developed and tip-in torque control is integrated to the model. For system identification data obtained from the test vehicles were used. Simulations were run and compared with the test data. Finally, feasibility and potential areas of future work are discussed.

Key Words: Engine Control, Drivability, Performance, Response Surface Methodology, Driveline Oscillations, Parameter Optimization

ÖZET

Otomotiv kontrol modüllerinde, sistem kontrolü için kalibrasyon parametreleri kullanılmaktadır ve ödünleşimlerden dolayı optimum performans için optimizasyon yöntemleri kullanılarak optimize edilmeleri gerekmektedir. Ancak parametre optimizasyonu aracın geliştirmesi aşamasında çok zaman alan bir adım olması yanı sıra üretimden sonra da gerekli hale gelmiştir. Araçların başlangıç performansları ve sürülebilirlikleri, kullanım mesafesi ve şartlarına bağlı olarak ortaya çıkan yıpranmalardan olumsuz etkilenir. Fakat mevcut motor kontrol ünitelerinin yazılım yapısı, güç aktarım sisteminin işleyişindeki değişikliklerin izlenmesine izin vermemektedir. Bu çalışmanın özgün yönü, mekanik aşınma ve yaşlanma nedeniyle meydana gelen olumsuz değişikliklere karşı aracın ömrü boyunca optimize edilmiş performans ve sürülebilirlik sağlayan ve sistemi kendi kendine kalibre etmesi prensibine dayanan bir algoritma önermesidir. Sürücü memnuniyeti için gerek sürülebilirlik gerekse performans özellikleri dikkate alınmalıdır. Araç değerlendirmeleri için nesnel metriklerin mevcut olmaması ve uygulamada öznel değerlendirme kullanılması nedeniyle, sürülebilirlik ve performans özelliklerinin onayı hem zaman almakta hem de uzmanlık gerektirmektedir. Çalışmanın benzerlerinden farklı bir diğer yönü, performans ve sürülebilirlik özellikleri için birleşik bir maliyet fonksiyonunun belirlenmesidir. Algoritmanın çalıştığını göstermek için yavaşlama esnasında gaz pedalına hızlı basış manevrası seçilmiş ve seçilen manevraya uygun deney tasarımı hazırlanarak küçük binek ve hafif ticari araçlarla kontrollü ortamda testler gerçekleştirilmiştir. Nesnel verilerle öznel değerlendirmeleri ilişkilendirmek için yanıt yüzeyi metodolojisi kullanılmış ve nesnel kriter fonksiyonları elde edilmiştir. Birleşik nesnel değerlendirme için, genel manevra notlandırması kriter notları ve her bir kriterin ağırlık faktörleri kullanılarak formüle edilmiştir. Optimizasyon için altın kesit algoritması kullanılmıştır. Önerilen metodoloji bir prototip araçta uygulanmış, araç değerlendirmeleri ve çevrimiçi optimizasyonda başarılı olduğu doğrulanmıştır. Ek olarak, araç ve elastik aktarma organları modeli geliştirilmiştir ve tork kontrol modeli ile entegre edilmiştir. Test araçlarından alınan veriler ile sistem tanımlama yapılmış ve geliştirilen model ile simülasyonlar koşularak test verileri ile karşılaştırılmıştır. Son olarak, fizibilite ve gelecekte yapılabilecek potansiyel çalışmalar tartışılmıştır.

Anahtar Kelimeler: Motor Kontrolü, Sürülebilirlik, Performans, Yanıt Yüzeyi Metodolojisi, Aktarma Organları Salınımları, Parametre Optimizasyonu

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LIST OF ABBREVIATIONS AND ACRONYMS

<i>app</i>	: Accelerator pedal position (%)
<i>app_ax_corr</i>	: Accelerator pedal and acceleration correlation (-)
<i>app_rate</i>	: Accelerator pedal position derivative (%/s)
<i>ax_osc_1</i>	: First longitudinal acceleration oscillation (m/s ²)
<i>ax_osc_2</i>	: Second longitudinal acceleration oscillation (m/s ²)
<i>ax_osc_3</i>	: Third longitudinal acceleration oscillation (m/s ²)
<i>ax_stab</i>	: Stabilized longitudinal acceleration (m/s ²)
<i>engspd_init</i>	: Initial engine speed (rpm)
<i>max_ax_grad</i>	: Maximum acceleration gradient (m/s ³)
Hz	: Hertz
kg	: Kilogram
kg/m ³	: Kilogram per meter cube
m/s	: Meter per second
m/s ²	: Meter per second square
Nm	: Newton meters
rpm	: Revolution per minute
<i>rstool</i>	: Interactive response surface modeling
<i>R²</i>	: The coefficient of determination
<i>a₀</i>	: Constant term in criterion rating formula
<i>a_i & a_{ij}</i>	: Linear and interaction terms coefficients
<i>n</i>	: Number of parameters
<i>x_(i,j)</i>	: Parameter values in criteria rating function
<i>L_l</i>	: Lower limit
<i>L_u</i>	: Upper limit
<i>gr</i>	: Golden ratio ($(\sqrt{5} - 1)/2$)
<i>t</i>	: Tolerance
<i>e₁ & e₂</i>	: Evaluation points
<i>in</i>	: Iteration number
<i>in_mx</i>	: Maximum iteration number
<i>f(e_i)</i>	: Function result at evaluation point <i>e_i</i>
<i>cr_i</i>	: Criterion rating
<i>w_i</i>	: Criterion weight
<i>w_T</i>	: Total of criteria weights
<i>cf_i</i>	: Correction factor
<i>F_{rl}</i>	: Road load (N)
<i>F_{aero}</i>	: Aerodynamic drag force (N)
<i>F_{rr}</i>	: Rolling resistance force (N)
<i>F_g</i>	: Road load due to road inclination (N)
<i>m_{tot}</i>	: Vehicle weight (kg)
<i>FA</i>	: Frontal area of the vehicle (m ²)
<i>ρ_{air}</i>	: Air density (kg/m ³)
<i>v</i>	: Vehicle velocity (m/s)
<i>g</i>	: Gravitational acceleration (m/s ²)
<i>α</i>	: Road inclination (rad)
<i>C_d</i>	: Aerodynamic drag coefficient
<i>f_r</i>	: Road friction coefficient

API	: Application Programming Interface
CAN	: Controller Area Network
DoE	: Design of Experiments
ECU	: Engine Control Unit
EGR	: Exhaust Gas Recirculation
EMS	: Engine Management Software
FDR	: Final Drive Ratio
FWD	: Front Wheel Drive
ICE	: Internal Combustion Engine
LCV	: Light Commercial Vehicle
MIL	: Model in the Loop
NVH	: Noise Vibration & Harshness
OBD	: On Board Diagnostics
OEMs	: Original Equipment Manufacturers
PCM	: Powertrain Control Module
PS	: Horsepower
PTW	: Performance Test Weight
RMSE	: Root Mean Square Error
RSM	: Response Surface Methodology
USB	: Universal Serial Bus
WOT	: Wide Open Throttle
WBV	: Whole-body Vibration

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1. INTRODUCTION

In almost every field there are trade-offs and optimization methods are needed to be applied for low cost and optimum performance. In automotive control modules, lookup tables are used for system control and parameter optimization has become a necessary step in development phase and due to degradation of system performance in time it is also expected while in use.

In automotive industry, original equipment manufacturers (OEMs) must comply to regulations which include many attributes such as emissions, durability, safety, and noise vibration & harshness (NVH) [Web 1, 2024]. However, apart from regulations, there are some attributes defined and considered as essential for customer point of view such as fuel economy, drivability, and performance. This dissertation mainly focuses on objective assessment criteria and online optimization algorithm development for drivability and performance attributes.

Drivability is defined as the driver's perception of driving quality; the ability to respond smoothly and responsively to the driver inputs, both in transient and steady state conditions. Over the last 3 decades there has been remarkable technological developments in the automotive industry. As a result of these improvements especially in electronics, materials science and manufacturing, internal combustion engines (ICE) torque, power and torque build up rate has increased significantly and makes vehicles capable of delivering high torque in a very short time to driver pedal inputs. Even though performance has been improved, these improvements in torque production reduced driving comfort and caused some error states such as jerks and driveline oscillations. Therefore, drivability attribute had gained significant importance for driver satisfaction.

For driver satisfaction both drivability and performance attributes must be considered, and combined assessment is required. Nevertheless, for these attributes, optimization takes time, incurs a considerable cost, and requires expertise since objective metrics are not available and generally subjective assessment is used for signoff. Therefore, one of the objectives of this thesis is to evaluate driving quality objectively based on analytical analysis, and determination of a combined cost function for performance and drivability attributes.

Additionally, during calibration of the engine control unit (ECU) software, results are heavily dependent on the measured data taken from prototype vehicles, chassis dynamometers and engine test beds. Furthermore, the initial performance and drivability of vehicles are adversely affected depending on the distance and conditions of use. However, current software structure does not allow tracking changes in system operation and cannot compensate for drift due to aging and mechanical wear. Consequently, there is a need for a learning algorithm that can update the parameters online yet does not require infeasible computational load and memory.

In this thesis, self-tuning algorithm is proposed to achieve varying performance and drivability metrics. Proposed control software achieves better performance over against varying metrics, parameter uncertainties and changes due to mechanical wear and aging in vehicle's powertrain. Proposed control structure can yield optimized performance throughout the life span of the system as well as reduce development time.

The flow chart of the processes, methods and algorithm development steps are given in **Figure 1.1**.

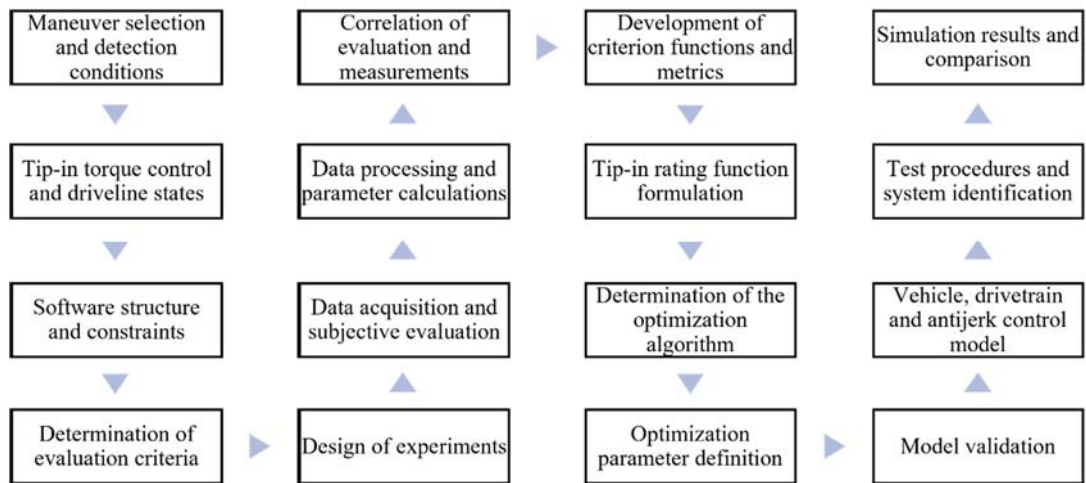


Figure 1.1: Process flowchart.

The study is structured in seven main chapters. In the second chapter, maneuver selection is described for performance and drivability attribute assessments, driveline states during torque control are investigated, torque control software structure is studied, and assessment criteria; acceleration delay, acceleration conformity, peak

acceleration gradient, and acceleration fluctuations; are defined. In the third chapter, test setup, test vehicles and instrumentation, subjective evaluation rating scale and design of experiments are determined, event detection algorithm is developed, and objective measurements, data processing and parameter calculations are performed. In the fourth chapter, correlation between objective measurements and subjective assessments is investigated. Response surface methodology is adopted for correlation. Criteria and tip-in rating functions are formulated, and criteria metrics are defined. In the fifth chapter, online optimization is performed. Golden section algorithm is used for optimization. The proposed methodology is applied, validated and results are presented. In the sixth chapter, vehicle model is developed, model parameters are tuned, and simulation results are compared with the test data. Finally, method performance, feasibility and potential areas of future work are discussed.

1.1 Motivation and Background

In the literature, there are many studies on vehicle assessments, vehicle control unit parameter optimization, driveline modelling and drivability control.

In order to assess vehicles, some researchers investigate vehicle dynamic performance [Zhao et al., 2018], and some studies focus on driving comfort [Zhang et al., 2020]. However, the trade-off between drivability and performance needs to be considered and combined assessment is required. In this dissertation, the correlation between subjective evaluations and objective measurements are investigated, and combined assessment considering all the criteria necessary for the evaluation of performance and drivability attributes has been carried out. Similar approaches can be seen in the field where to assess ergonomics and dynamic comfort, correlation between objective measurements and subjective assessments is used [Ao et al., 2020].

There are many studies carried out on the hardware design and analysis for driveline components to improve driving comfort [Genç and Kaya, 2020]. This study focuses on software development rather than hardware development for driving comfort and performance improvement.

Some researchers investigate driveline modelling to develop new control algorithms to improve drive comfort. Most of the research is based on plant parameters to model the system as accurate as possible since performance of the controller depends on the

accuracy of the system model [Pham and Bushnell, 2015]. Model-based methods require precise dynamic engine and driveline model for drivability. However, complexity of automotive control is gradually increasing with new actuators, and this makes establishing the physics model of the system according to the basic physical principles very difficult so data and physics hybrid modeling and controlling methods are considered as future direction of automotive control with vital practical value and scientific significance [Fang et al., 2013]. In some of the model-based studies, results are promising yet fine tuning should still be carried out during test rides by calibration engineers [Mayr et al., 2014]. In this thesis, vehicle tests were carried out in criteria development and optimization studies to fully represent the engine and vehicle characteristics. In addition to these, an elastic driveline model is developed within the scope of the presented work for the purpose of assessing drivability and performance attributes. Model parameters are tuned with the data taken from test vehicles. Then developed vehicle model is integrated with proposed self-tuning algorithm, and the results of vehicle tests and simulation results were compared.

After criteria functions and tip-in rating function development, optimization is studied online in test vehicles. Parameter determination is very important for optimization. Sensitivity analysis of parameters used in control software is another area of interest for engine calibration optimization. The contribution of each input in influencing the engine output is not solely based on same input and change by altering other operational parameters. There are studies investigating the relative effect of each input while other parameters are fixed [Nikzadfar and Shamekhi, 2014]. In this study, optimization is studied through the control of the rate of change of torque.

Lastly, there has been also some research on using dynamic tables and adaptive modelling; and these studies are promising on using adaptive strategies for system modelling in commercial control modules [Guardiola et al., 2013]. In addition, there has been research on an iterative learning control approach for ECU calibration maps [Caporale et al., 2015; Min et al., 2018]. As the main scope for this thesis, it is of interest to investigate how such learning algorithms could be used in online operation of the engines to automatically update the calibration maps over time, refining the engines performances despite degradation of its components.

1.2 Significance & Unique Aspect

Objective evaluation of drivability and performance attributes is one of the main challenges in the field. Unlike many attributes where metric is chosen as error that is calculated from a measured signal and its desired value, objective metrics are not readily available for drivability and performance attributes. In general, evaluations are performed subjectively by technical specialists and driving experts. To overcome this issue, this study investigates the correlation between subjective assessments and objective measurements, and successfully defines assessment criteria and formulates criteria functions.

To fully represent the actual engine and vehicle characteristics, this study includes actual vehicle testing. For objective assessments, ECU signals and longitudinal acceleration measurements are used, and assessment is based on measured and calculated parameters, and is done by means of drive rating from 1 to 10. The proposed methodology is simple and proved to be effective for combined objective evaluation of drivability and performance attributes. It also includes metric determination from dominant parameters for fast and approximate results.

Another unique aspect of the thesis is optimization is performed online as lookup tables will be updated over time to overcome parameter uncertainties and changes due to mechanical wear and aging. By this means proposed self-tuning algorithm yields optimized performance and drivability throughout the life span of the vehicle.

The unique aspects and contributions of this study can be summarized as follows:

- Formulating a combined objective assessment of drivability and performance attributes and ensuring that subjective drivability assessments that require expertise can be made objectively.
- Development of an algorithm that provides optimized performance and drivability throughout the life span of the vehicle against adverse changes in vehicle driving quality due to mechanical wear and aging.
- Determination of metrics from the dominant parameters for fast and approximate results.
- The potential for use in a motor control unit due to the ease of implementation of the proposed algorithm and its compliance with processor and memory requirements.

- The developed methodology is suitable for diagnostic purposes to monitor changes in system operation.

1.3 Data Acquisition and Processing Tools

Required software and hardware is determined for planned studies throughout the thesis. For engine control unit connection, data acquisition, data analysis and parameter optimization, MATLAB and ATI Vision software is selected.

ATI Vision software is an integrated calibration and data acquisition tool that provides direct access to the controller area network (CAN), provides interface to the ECU, and allow data recording and parameter adjustments. It can also collect signals from external sources, measures relationships between inputs and outputs, enables real-time calibration and programs the ECU [Web 2, 2024].

Additionally, MATLAB is used for parameter calculations, signal processing, optimization, and modelling. MATLAB is the high-level language and interactive environment used by millions of engineers and scientists worldwide. [Web 3, 2024].

Kvaser Leaf Light is used as hardware interface to the ECU. It is a reliable low-cost product that supports full speed universal serial bus (USB) interface for CAN with high performance. Loss free transmission and reception of standard and extended CAN messages on the CAN bus is transmitted with a time stamp precision of 100 microseconds. Application areas are human interfaces and testing equipment [Web 4, 2024].

For high resolution acceleration measurements, MEMSIC CXL04GP3-R-AL model accelerometer is used. Common applications include automotive testing, instrumentation, and equipment monitoring [Web 5, 2024].

2. TORQUE CONTROL SOFTWARE & ASSESSMENT CRITERIA

In this chapter, maneuver selection is described for performance and drivability attribute assessments, driveline states during torque control are investigated, torque control software structure is studied, and assessment criteria; acceleration delay, acceleration conformity, peak acceleration gradient and acceleration fluctuations; are defined.

2.1 Maneuver Selection

There are different maneuvers that could be performed in the vehicle such as launch, acceleration, deceleration, tip-in, tip-out, gearshift, cruise and drive away. An increase or decrease in engine torque is the cause of many drivability concerns. The torque change could be caused by driver torque demand change via accelerator pedal, change in engine speed by either a gearshift or acceleration/deceleration or change in airflow through the engine. The corresponding increase or decrease in torque travels through the driveline interacting with powertrain and other vehicle subsystems that may react to the increased torque disturbance with increased vibration or noise.

In this study, the drivability issues during load changes; tip-in and tip-out maneuvers; performed by the driver are investigated. Tip-in maneuver is described as pressing accelerator pedal with high pedal rate during deceleration, and tip-out maneuver is described as releasing accelerator pedal during acceleration. Tip-in and tip-out are main maneuvers for drivability and performance evaluations. This is because automotive drivelines are composed of elastic parts such as clutch, flywheel, gears, and drive shafts, and torsional vibrations occur during torque transitions especially during tip-in and tip-out maneuvers due to the flexibility of the drivetrain components. The typical resonance frequencies of the drivetrain in vehicles are in the range of 1 and 10 Hz. [Fredriksson et al., 2002; Bruce et al., 2005; Figel et al., 2019; Scamarcio et al., 2020]. Driveline oscillations at 2 Hz and above are felt by the drivers and can cause discomfort and injury [Cheung and Nakashima, 2006]. Another recent study revealed that vibrations frequencies up to 12 Hz have a great influence on human body parts and organs, and the discomfort increases with the amplitude of the vibration

[Kauraw et al., 2023]. With the high torque change rates on the drivetrain, the amplitude of these oscillations can increase and become perceptible to the driver [Figel et al., 2019]. Therefore, evaluation of driveline induced oscillations as well as response delay, acceleration profile with respect to pedal input and jerks are critical for drivability and performance assessments. To demonstrate method performance, tip-in maneuver is selected which encompass tip-out maneuver as well since the only differentiating factor between these maneuvers is the direction of torque change. Based on selected maneuver, event detection algorithm is developed. Details of event detection conditions are given in Chapter 3.4.

2.2 Tip-in Torque Control

In engine management software (EMS), there is a torque filtering function, anti-jerk controller, to control and shape torque during tip-in and tip-out maneuvers to prevent oscillations from occurring [Scamarcio et al., 2020]. Since apart from the material stress, these oscillations adversely affect both performance and drivability [Baumann et al., 2006]. In particular, the damping of oscillations that may occur in the vehicle is necessary for driving comfort and driver satisfaction [Fredriksson et al., 2002].

Torque filtering function controls torque when the driver requested torque is greater or lower than the current torque. Anti-jerk control reduces the longitudinal vehicle acceleration oscillations, also called shuffles [Salle et al., 2004], that would compromise vehicle comfort and drivability, and could affect drivetrain component durability [Götting and Kretschmer, 2013].

The backlash in the automotive drivetrain has a significant impact on the response of the system. The backlash causes oscillations when the torque changes sign and negatively affects driving comfort [Canova et al., 2017; Reddy et al., 2022]. The torque sign change; the driveline approaching and crossing backlash from negative torque to positive torque or vice versa; occurs in the event that the accelerator pedal is not pressed, and the engine produces a positive torque by pressing the accelerator pedal at least enough to overcome the negative torque due to engine friction, accessories, driveline torque losses, and road load or in the event that the accelerator pedal is depressed and produces a positive torque, and engine stops torque production by releasing the accelerator pedal.

Torque control is done based on driveline states; pre-lash, in-lash, and post-lash. The purpose of torque control in pre-lash during transition from negative torque to positive torque is to manage how quickly the driveline transitions from negative torque to zero torque. When the torque that is being applied by the engine to the driveline is zero, the driveline is in-lash. During in-lash phase, torque is not transmitted due to the mechanical interface. It is of critical importance to optimize torque rise/decrease rate as the driveline approaches and crosses backlash from negative torque to positive torque and vice versa to prevent error states such as oscillations and sag while minimizing hesitation. In post-lash phase, tip-in control ramps torque towards driver demand until driver demand is reached. Driveline states and torque-angular displacement relationship in each state is shown in **Figure 2.1** [Furlich et al., 2022].

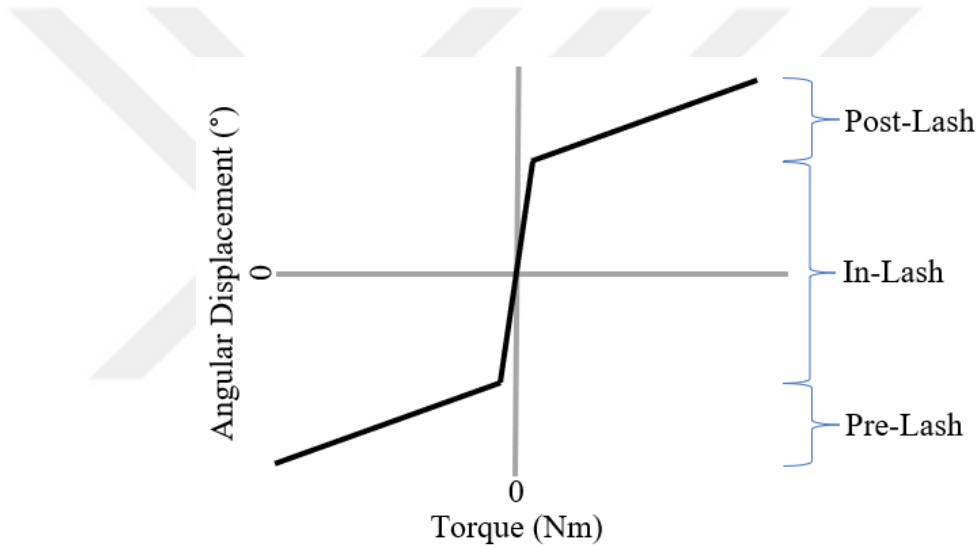


Figure 2.1: Driveline states [Furlich et al., 2022].

2.3 Software Structure and Constraints

Labels are lookup maps, curves or scalars in control software that must be calibrated for optimum performance. In tip-in torque control software at hand, main labels that need to be optimized are lookup maps that are based on instantaneous torque, accelerator pedal, engine speed and gear.

In software used for this study, there are accelerator pedal and engine speed based maps for each gear, and there is also a map based on instantaneous torque and gear, and these maps' outputs are multiplied and instantaneous torque rate is calculated.

In order to minimize shuffle in the drivetrain, torque rate is reduced during lash crossing, and during pre-lash and post-lash phases torque rate is increased to reduce hesitation and to get expected performance. However, if torque rate is set to a low value there is hesitation risk and lack of performance feel. On the other hand, if torque rate is high especially during lash crossing there is risk of shuffle, surge, clunk and even thump error states. Thump error state occurs when mechanical components hit each other, and it is felt by drivers as impact noise and harsh response.

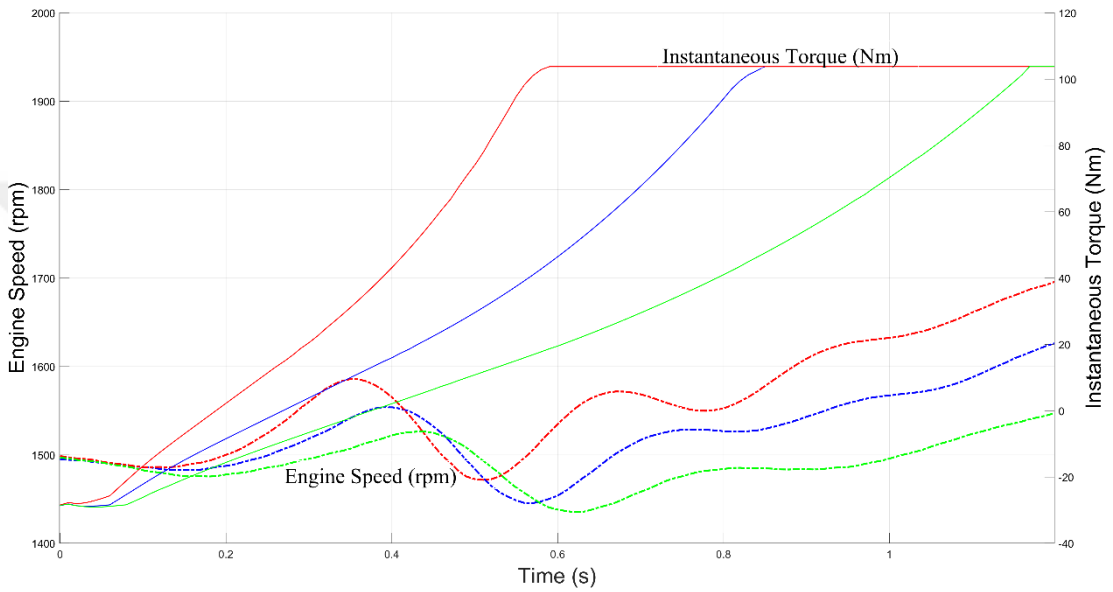


Figure 2.2: Comparison of different torque rates.

As an example, tip-in maneuvers at 1500 rpm engine speed with 50% accelerator pedal in 2nd gear with different torque increase rates are performed with a test vehicle, and results are shown in **Figure 2.2**. Torque rate is increased consecutively, set to 600 Nm/s, 1800 Nm/s and 3000 Nm/s sequentially, and resultant engine speed and instantaneous torque demand signals are shown as green, blue, and red lines respectively in the figure. With very low torque rate shuffle amplitudes are very low; however, performance is poor. On the other hand, when torque rate is set to very high value, performance is good; however, shuffle amplitudes are high. This example shows that torque rate related labels in the control software should be calibrated and optimized to get optimum comfort and performance.

2.4 Criteria Determination

Not only driving comfort but performance is also critical for customer satisfaction, and main driving quality determinants for drivers are acceleration and change in the acceleration. Therefore, it is decided that acceleration profile, overall performance feel, response time of the vehicle to driver inputs, sudden acceleration changes, sags and oscillation amplitudes are main attributes that needs to be considered for objective assessment. As a result, 4 criteria are determined for drivability and performance assessment and optimization in the vehicle: “Acceleration Delay”, “Acceleration Conformity”, “Peak Acceleration Gradient” and “Acceleration Fluctuations”.

Acceleration delay and acceleration conformity criteria are considered for performance evaluation, and peak acceleration gradient and acceleration fluctuations criteria are considered for drivability evaluation.

“Acceleration Delay” criterion evaluates the vehicle's reaction time to the driver's accelerator pedal input. "Acceleration Conformity" criterion is defined as the conformity of acceleration and accelerator pedal position. “Peak Acceleration Gradient” is criterion that assesses the rate of change of longitudinal acceleration. “Acceleration Fluctuations” is the criterion that assesses oscillations in acceleration after peak acceleration gradient. Parameters used for calculation of criteria functions are given in section 3.5 and details of each criterion and function formulations are given in Chapter 4.2.

3. VEHICLE ASSESSMENTS & DATA

PROCESSING

In this chapter, test vehicles and instrumentation, subjective evaluation rating scale and design of experiments are determined, event detection algorithm is developed, and objective measurements, data processing and parameter calculations are performed.

3.1 Test Vehicles and Instrumentation

Assessments are performed with small passenger vehicles and a light commercial vehicle (LCV). The detailed vehicle specifications are listed in **Table 3.1**. Tests are performed in a test track on flat road, and test conditions; no wind and 20-25°C ambient temperature; are monitored to ensure same conditions for comparable results.

Table 3.1: Specifications of the test vehicles.

Specification	Vehicle #1	Vehicle #2	Vehicle #3
Vehicle Class	LCV	Passenger	Passenger
Model	Courier	Figo	Fiesta
Engine	1.5l DV5FD	1.5l DV5D	1.5l DV5FC
Rated Horsepower (PS)	85 PS	100PS	120PS
Maximum Torque (Nm)	215Nm	215Nm	285Nm
Emission Level	Euro 6	Euro 6	Euro 6
Transmission	6 speed - 6MX65	5 speed - 5MX65	6 speed - iB6
Final Drive Ratio (FDR)	3.55	3.37	3.35
Powertrain Test Weight (kg)	1450kg	1280kg	1290kg
Tire Dimensions	195/60R15	185/55R15	195/55R16

During vehicle testing and evaluations, measurements are taken from engine control unit and accelerometers are instrumented in test vehicles for high resolution longitudinal acceleration. For objective evaluations, engine speed, vehicle speed, accelerator pedal position, engine torque, brake pedal and gear signals were taken from the engine control unit during vehicle tests.

ATI Vision, a commercial software, is used to take measurements from the engine control module and instrumentation, and MATLAB is used for data processing and calculations. The data collection and processing flowchart is shown in **Figure 3.1**.

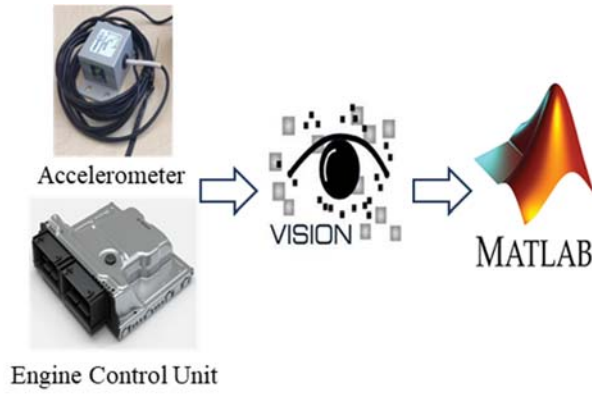


Figure 3.1: Flowchart of data acquisition and processing.

3.2 Subjective Evaluation Rating Scale

Subjective evaluation rating scale is defined for performance and drivability attributes based on most customer expectations, rating from 1 to 10. Rating 1 means performance is not acceptable, and customer is very dissatisfied with the vehicle. Rating 10 means performance is excellent, and customers are completely satisfied with the vehicle. Ratings 9 & 10 are only perceptible to critical customers and driving experts. Rating 6 is defined as borderline acceptable for performance and drivability.

Subjective evaluation rating scale is given in **Table 3.2**.

Table 3.2: Subjective evaluation rating scale.

Rating Scale	1	2	3	4	5	6	7	8	9	10
Performance	Not Acceptable		Very Poor		Poor	Borderline	Acceptable	Good	Very Good	Excellent
Drivability					Dissatisfied	Somewhat Dissatisfied	Satisfied	Very Satisfied	Completely Satisfied	

Most of the drivers are satisfied with the vehicle with a rating equal to or greater than 7.0. Drivers begin to be dissatisfied with the vehicle with a rating below 6.5, and as the ratings decrease, the level of satisfaction decreases.

3.3 Design of Experiments

For drive experts' evaluations design of experiments (DoE) is prepared, and evaluations are performed with small passenger vehicles and a light commercial vehicle on a test track. For each gear, 4 levels of accelerator pedal position and starting from 1000rpm up to 3000rpm depending on gear 4 to 6 levels of initial engine speeds are used with 500rpm intervals for low gears and 250rpm intervals for high gears. Multiple tests were performed for each point with varying accelerator pedal position rates and torque rates to improve model accuracy.

Ratings are given with 0.25 resolution by drive experts. Drive experts takes both performance and customer satisfaction into consideration during rating determination. Each criterion is rated separately, and evaluation results are discussed among experts and joint decision, or average of evaluation rating values are used for criteria function calculations.

3.4 Event Detection

Event detection algorithm is developed based on the conditions given in **Table 3.3**.

Table 3.3: Event detection conditions.

Initial acceleration level $< 0 \text{ m/s}^2$
Transmission is in gear
Delta pedal position must be at least 10%
Accelerator pedal rate (tip-in pedal rate) $> 150 \text{ \%/sec}$
The event must be at least 2 seconds
The event is not valid if brake pedal is applied within 2 sec after accelerator pedal is pressed
Longitudinal acceleration must be at least 0.2 m/s^2 and acceleration gain is at least 0.5 m/s^2

3.5 Signal Processing and Parameter Calculations

Measurements taken from the vehicles are analyzed and for objective evaluation parameters are determined considering acceleration profile, response time of the vehicle to driver pedal inputs, sudden acceleration changes, sags, and oscillation amplitudes. Parameters are calculated variables that are derived by using available signals and their processed versions or derivatives. They are used to determine test conditions and quantify performance and driving comfort for a tip-in maneuver.

Signals processing; low pass filter and moving average algorithms; is also applied on engine speed and acceleration signals to be used for parameter calculations. For driveline induced oscillations frequency range from 1 Hz to 10 Hz is taken into account in this research. Processed signals are given in **Table 3.4**.

Table 3.4: Processed signals.

Processed Signals	Descriptions
ax_mave (5) diff	Derivative of smoothed acceleration
ax_LP (10)	Low pass filtered acceleration
ax_mave (20)	Moving average of acceleration
engspd_mave (20)	Moving average of engine speed

Additionally, for functionality & hardware protection and limitation checks, as well as force, torque, speed and acceleration calculations and conversions vehicle, engine, and transmission information is used, which is given in **Table 3.5**.

Table 3.5: Vehicle, engine, and transmission information.

Full Load Torque Curve (Nm)
Engine Friction Curve (Nm)
Total Crankshaft Inertia (kg.m ²)
Transmission Gear Ratios
Gearbox Torque Limits (Nm)
Vehicle Mass (kg)
Wheel Rolling Radius (m)
Frontal Area (m ²)
Aero Drag Coefficient (-)
Road Resistance Coefficient (-)

For each evaluation criterion required parameters are determined. Parameter list and criteria mapping is given in **Table 3.6**.

Table 3.6: Parameter table.

Parameter	Description	Acceleration Delay	Acceleration Conformity	Peak Acceleration Gradient	Acceleration Fluctuations
app	accelerator pedal position	x	x	x	x
app_ax_corr	pedal acceleration correlation		x		
app_rate	accelerator pedal rate			x	x
ax_osc_1	first ax oscillation				x
ax_osc_2	second ax oscillation				x
ax_osc_3	third ax oscillation				x
ax_stab	stabilized acceleration	x	x	x	x
engspd_init	initial engine speed	x	x	x	x
gear	gear	x	x	x	x
max_ax_grad	max acceleration gradient			x	
response_delay	response delay	x			

Accelerator pedal position, initial engine speed and gear parameters are derived by simple calculations using related input signals. Accelerator pedal rate is calculated by taking the derivative of the accelerator pedal position, and stabilized acceleration is calculated as the settled acceleration value of the vehicle after the oscillations are damped. Remaining parameters are response time, pedal acceleration correlation, maximum acceleration gradient, and oscillation amplitudes which are dominant parameters for evaluation criteria.

Accelerator pedal position, stabilized acceleration, initial engine speed, and gear parameters are used in all criteria calculations. Accelerator pedal rate is used for drivability criteria. Response delay parameter is used for acceleration delay criterion, pedal acceleration correlation is used for acceleration conformity criterion, acceleration oscillation amplitudes are used for acceleration fluctuations criterion, and maximum acceleration gradient is used for peak acceleration gradient criterion.

Response delay is the main parameter for acceleration delay criterion, and it is formulated as the time duration between pedal input time and time when vehicle reaches 0.5 m/s^2 delta longitudinal acceleration as shown in **Figure 3.2**.

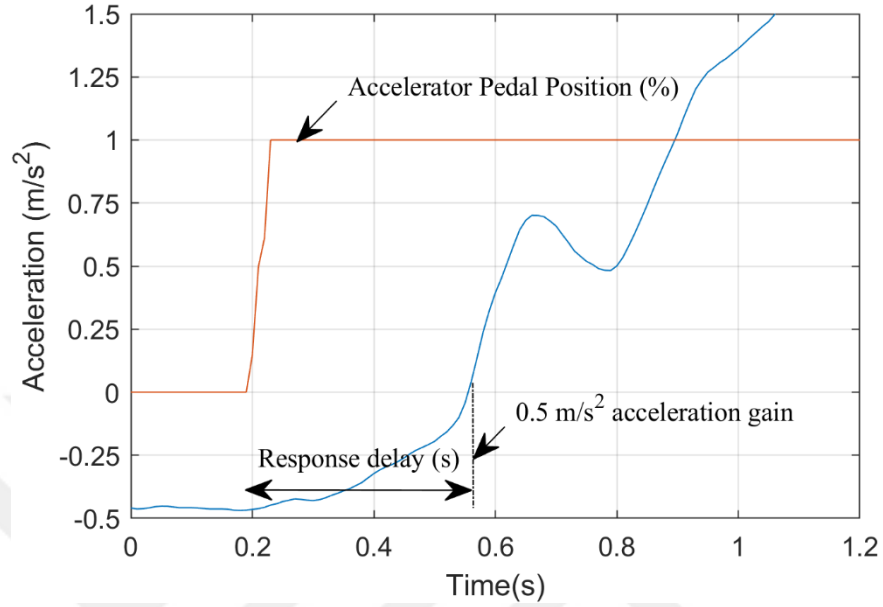


Figure 3.2: Response delay.

Pedal acceleration correlation is the main parameter for acceleration conformity criterion and formulated as ratio of areas under the normalized accelerator pedal and the normalized longitudinal acceleration as shown in **Figure 3.3**.

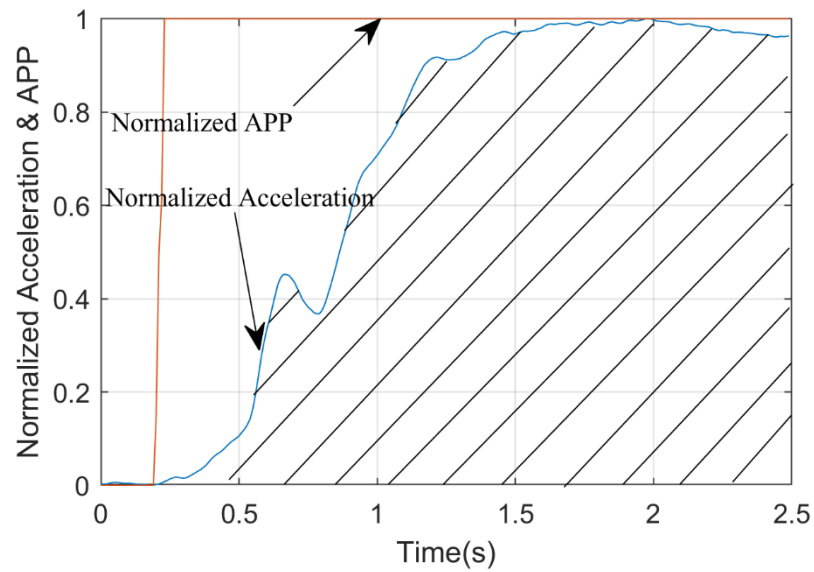


Figure 3.3: Pedal acceleration correlation.

Maximum acceleration gradient, shown in **Figure 3.4**, is the main parameter for peak acceleration gradient criterion.

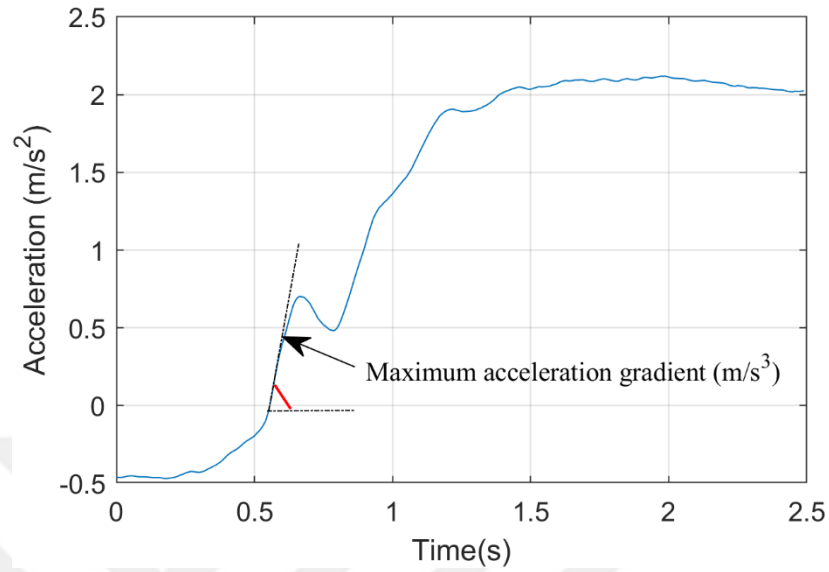


Figure 3.4: Maximum acceleration gradient.

First 3 oscillation amplitudes in acceleration, shown in **Figure 3.5**, are calculated from processed acceleration signal to be used for acceleration fluctuations criterion.

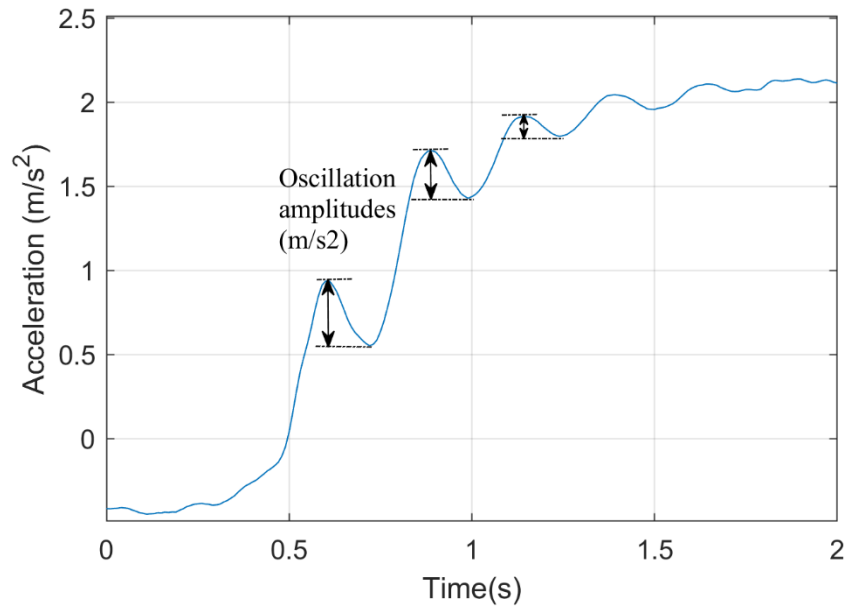


Figure 3.5: Acceleration oscillation amplitudes.

Some of the parameter calculations for a tip-in event in 2nd gear at 1500rpm with 50% accelerator pedal position are shown in **Figure 3.6**.

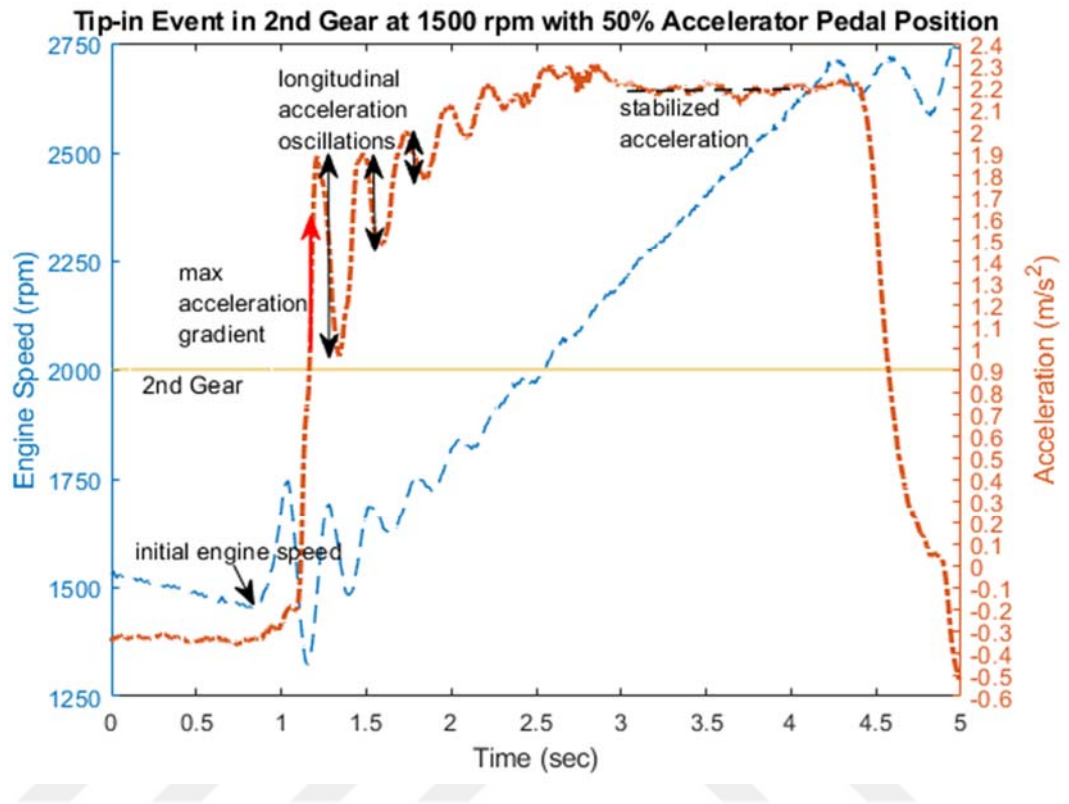


Figure 3.6: Parameters during a tip-in event.

4. CORRELATION BETWEEN OBJECTIVE MEASUREMENTS and SUBJECTIVE ASSESSMENTS

In this chapter, first brief description of response surface methodology is given. Subsequently, response surface methodology is adopted for correlation between objective measurements and subjective assessments, and criteria functions are formulated. Additionally, criteria metrics are obtained via analyzing linear dependence of dominant parameters to criteria ratings.

4.1 Response Surface Methodology

The response surface methodology (RSM), first developed by Box and Wilson, has been used to formulate criterion rating functions [Box and Wilson, 1951]. The response surface methodology is a collection of statistical and mathematical techniques used to model responses influenced by multiple independent variables [Montgomery, 2019]. RSM is a powerful tool for designing experiments and optimizing systems with multiple input variables. The fundamental concept underlying response surface methodology is to construct a mathematical model that identifies the correlation between the input variables and the response variable. This is achieved by conducting a series of experiments and collecting data on the response for various combinations of input variables. The collected data is then analyzed to identify the key input variables and their impact on the response.

4.2 Criteria Functions

The subjective evaluation results of the driving experts were given as the response variable, and the measured signals and calculated parameters were given as independent variables to the response surface methodology. RSM provides a model to evaluate the effects of several factors, and MATLAB's interactive response surface modeling (rstool) function is used to obtain rating functions. Related parameters for each criterion are selected as inputs to the interactions model that includes constant, linear, and interaction terms.

$$a_0 + \sum_{i=1}^n a_i x_i + \sum_{i=1}^n \sum_{j=2, j \neq i}^n a_{ij} x_i x_j \quad (4.1)$$

Criteria rating function formulation is given in equation (4.1) in which n is number of parameters, a_0 is the constant term, a_i and a_{ij} are the linear and interaction terms coefficients respectively, and $x_{(i,j)}$ are parameter values where i and j are denoted for number of parameters.

As an example, the three-parameter criterion function will be in the form of equation (4.2).

$$a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + a_{12} x_1 x_2 + a_{13} x_1 x_3 + a_{23} x_2 x_3 \quad (4.2)$$

Detailed analysis of each criterion is given in subsections. For each criterion, a sequence of plots is displayed, each showing a contour of the response surface against a single predictor, with all other predictors held fixed. rstool also plots a 95% simultaneous confidence band for the fitted response surface as two red curves. Additionally, objective rating calculations with respect to subjective assessment ratings for each criterion are displayed.

For validity of response surface models, the coefficient of determination (R^2) and root mean square error (RMSE) values are used. For all criteria, RMSE of residuals are below 0.255 and R^2 values are above 0.925 which shows strong relationship between objective measurements and subjective assessments.

4.2.1 Acceleration Delay

Acceleration delay criterion assesses response time of the vehicle to driver's accelerator pedal input. Parameters used for acceleration delay rating function are engine speed, accelerator pedal position, gear, stabilized acceleration, and response delay. Response delay is the dominant parameter for acceleration delay criterion, and it is formulated as the time duration between pedal input time and time when vehicle reaches 0.5 m/s² delta longitudinal acceleration.

Response surface model plots for acceleration delay criterion are given in **Figure 4.1**. It is seen that for same response delay times, criterion is rated higher for low initial engine speeds, low gears, and low stabilized accelerations.

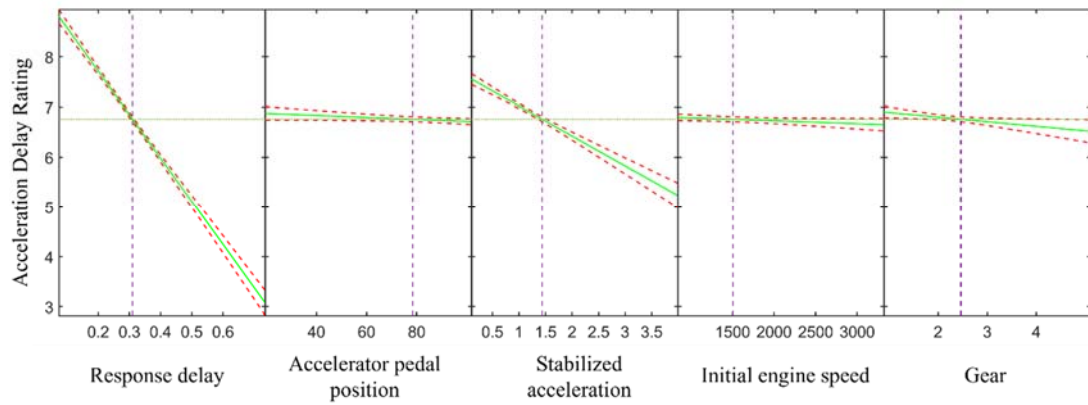


Figure 4.1: One-dimensional contours of multidimensional response surface model of acceleration delay.

Additionally, objective rating calculations with respect to subjective assessment ratings for acceleration delay criterion is given in **Figure 4.2**. R^2 value is 0.9267 and RMSE value is 0.231 that shows strong correlation between subjective assessments and model results.

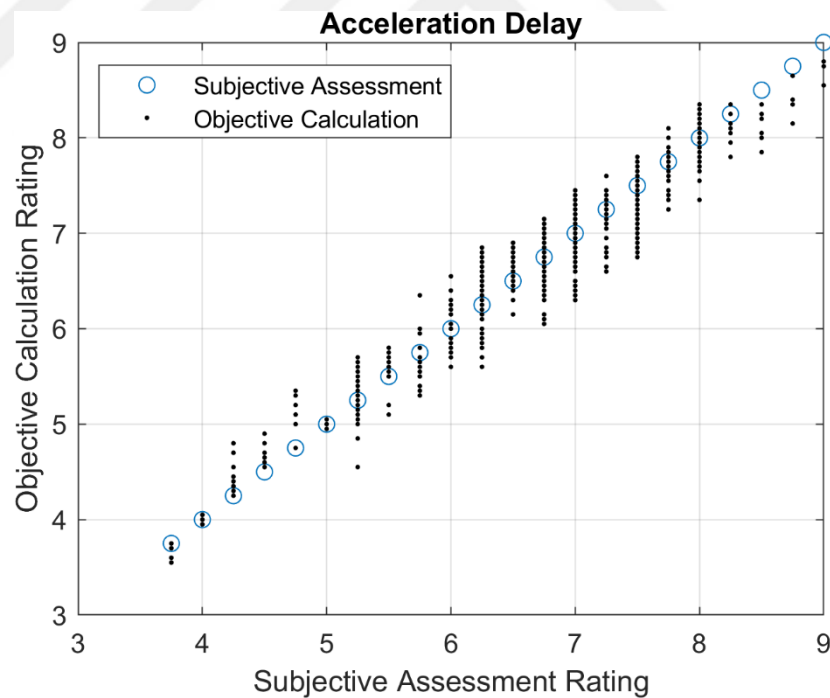


Figure 4.2: Acceleration Delay – Subjective assessment rating vs objective calculation rating.

4.2.2 Acceleration Conformity

Acceleration conformity criterion is defined as conformity of acceleration and accelerator pedal position. Parameters used for acceleration conformity rating function are engine speed, accelerator pedal position, gear, stabilized acceleration, and pedal acceleration correlation which is the dominant parameter. It is formulated as ratio of areas under the normalized accelerator pedal and the normalized longitudinal acceleration.

Response surface model plots for acceleration conformity criterion are given in **Figure 4.3**. It is seen that for same pedal acceleration correlation values, criterion is rated higher for low initial engine speeds and low stabilized accelerations.

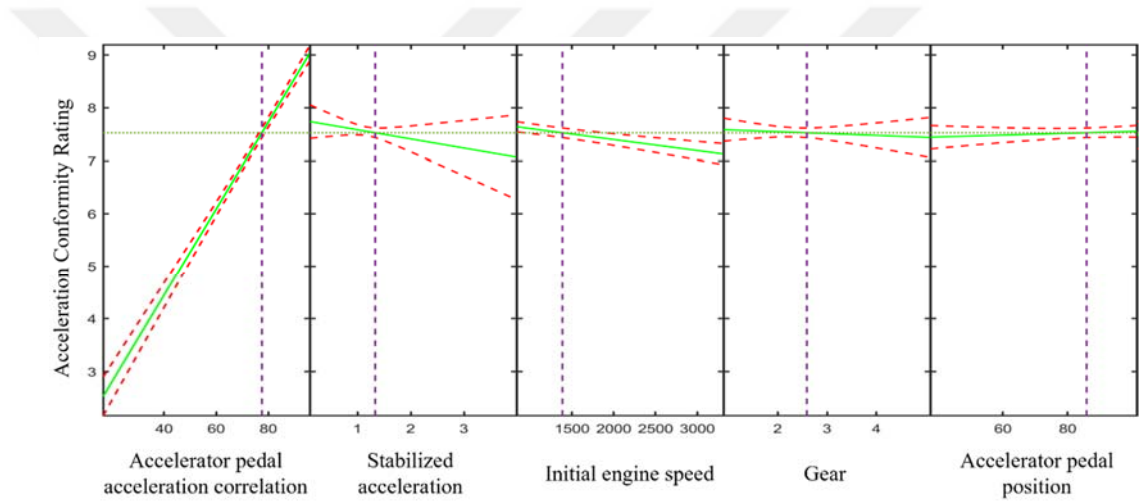


Figure 4.3: One-dimensional contours of multidimensional response surface model of acceleration conformity.

Furthermore, objective rating calculations with respect to subjective assessment ratings for acceleration conformity criterion is given in **Figure 4.4**. R^2 value is 0.9901 and RMSE value is 0.1139 that shows very strong correlation between subjective assessments and model results.

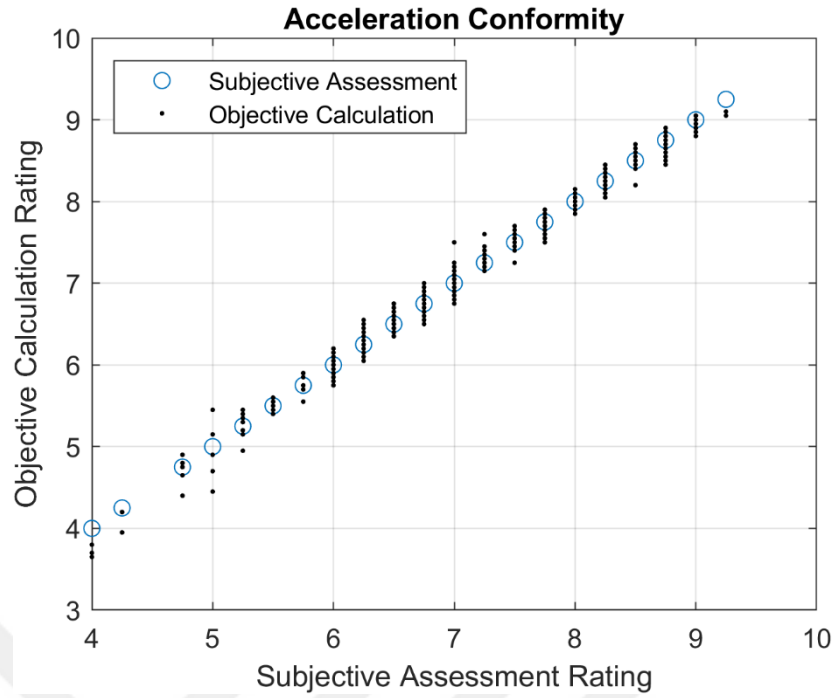


Figure 4.4: Acceleration Conformity – Subjective assessment rating vs objective calculation rating.

4.2.3 Peak Acceleration Gradient

Peak acceleration gradient is the criterion that assesses gradient of longitudinal acceleration. Response surface model plots for peak acceleration gradient criterion are given in **Figure 4.5**.

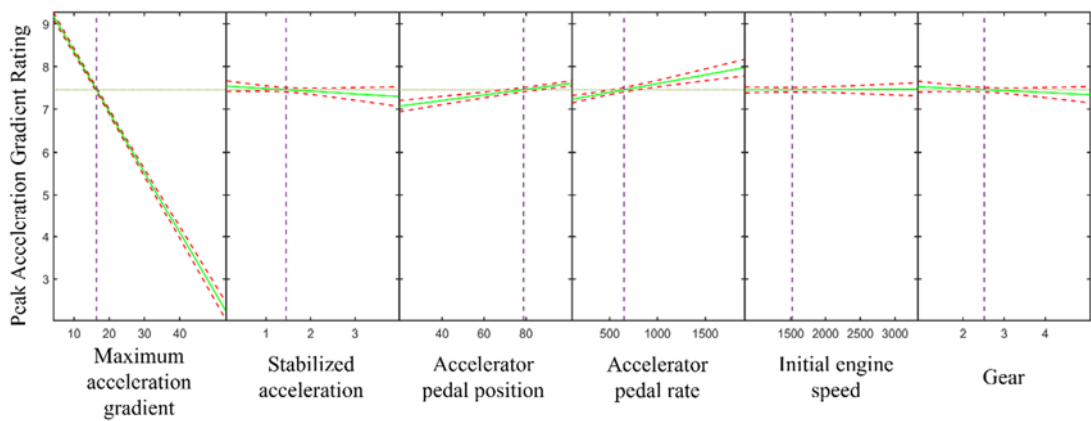


Figure 4.5: One-dimensional contours of multidimensional response surface model of peak acceleration gradient.

Parameters used for peak acceleration gradient rating function are engine speed, accelerator pedal position, accelerator pedal rate, gear, stabilized acceleration, and maximum acceleration gradient which is the dominant parameter. It is observed that for same maximum acceleration gradient values, criterion is rated higher for high accelerator pedal positions, high pedal gradients and low gears.

Moreover, objective rating calculations with respect to subjective assessment ratings for peak acceleration gradient criterion is given in **Figure 4.6**. R^2 value is 0.9708 and RMSE value is 0.1851 that shows strong correlation between subjective assessments and model results.

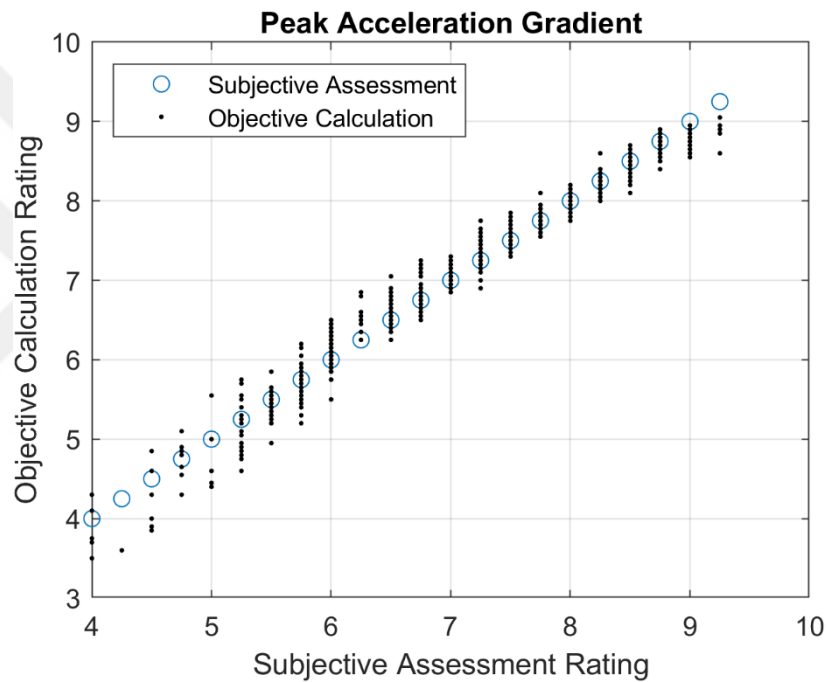


Figure 4.6: Peak Acceleration Gradient – Subjective assessment rating vs objective calculation rating.

4.2.4 Acceleration Fluctuations

Acceleration fluctuations is the criterion that assesses oscillations in acceleration. Parameters used for acceleration fluctuations rating function are engine speed, accelerator pedal position, accelerator pedal rate, gear, stabilized acceleration, and first three oscillation amplitudes. Main parameter for this criterion is first negative oscillation amplitude, which can be also called sag, yet other oscillation amplitudes also have significant effect on rating calculation.

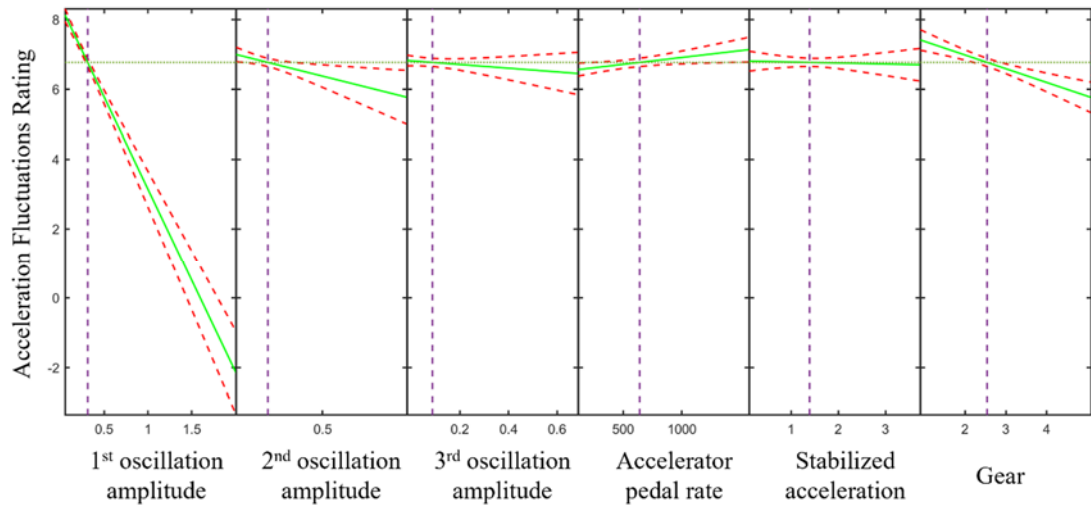


Figure 4.7: One-dimensional contours of multidimensional response surface model of acceleration fluctuations.

Response surface model plots for acceleration fluctuations criterion are given in **Figure 4.7**. It is seen that for same first oscillation amplitudes, criterion is rated higher for high accelerator pedal rates and low gears.

Additionally, objective rating calculations with respect to subjective assessment ratings for acceleration fluctuations criterion is given in **Figure 4.8**. R^2 value is 0.9252 and RMSE is 0.2531 that shows strong correlation between subjective assessments and model results; however, this correlation is not as strong as in other criteria.

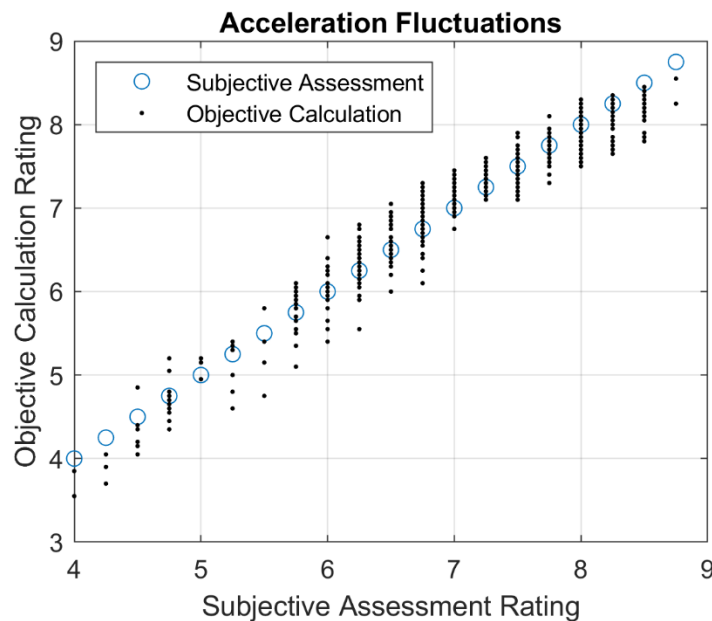


Figure 4.8: Acceleration Fluctuations – Subjective assessment rating vs objective calculation rating.

4.3 Criteria Metrics

Apart from criteria rating functions, assessment results are analyzed to determine linear dependance of each parameter to evaluation ratings, and metrics are obtained for each criterion using dominant parameters. Metrics and borderline acceptable parameter values are defined based on effects of other parameters and scattering of dominant parameters around target ratings. Events that satisfy the metrics but have lower ratings than the target ratings are also reviewed during metric determination. Metrics could be useful for researchers and calibration engineers for fast and effortless yet approximate assessment without any need of intensive calculations.

Acceleration delay metric function, given in equation (4.3), is obtained by fitting a 2nd order polynomial to experts' evaluations results with respect to response delay parameter as shown in **Figure 4.9**.

$$4.4335 x^2 - 11.583x + 10, 0 \leq x \leq 1 \quad (4.3)$$

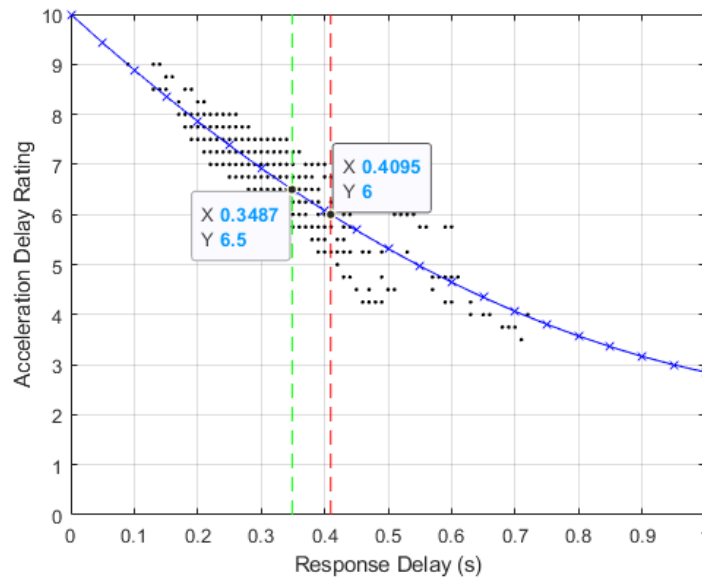


Figure 4.9: Acceleration delay metric function.

Acceleration delay metric is determined as response delay has to be smaller than 0.3487 second where trendline crosses rating 6.5 and as borderline acceptable level, it must not be above 0.4095 second which corresponds to rating 6.0.

Acceleration conformity metric function, given in equation (4.4), is obtained by fitting an exponential function to objective evaluation results with respect to pedal acceleration correlation (accelerator pedal position and acceleration correlation) parameter values as shown in **Figure 4.10**.

$$3.1025 \exp^{0.0114 x}, 10 \leq x \leq 100 \quad (4.4)$$

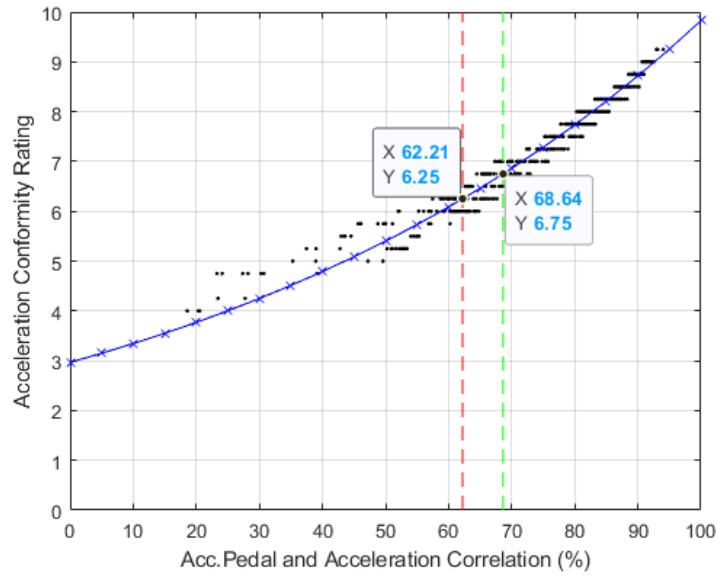


Figure 4.10: Acceleration conformity metric function.

Acceleration conformity metric is determined as pedal acceleration correlation has to be greater than 68.64% which corresponds to rating 6.75 on the trendline and as borderline acceptable level, it must not be below 62.21% that corresponds to rating 6.25.

Peak acceleration gradient metric function, given in equation (4.5), is obtained by fitting a 2nd order polynomial to experts' evaluations results with respect to maximum acceleration gradient parameter as shown in **Figure 4.11**.

$$0.0012 x^2 - 0.1778x + 10, 0 \leq x \leq 70 \quad (4.5)$$

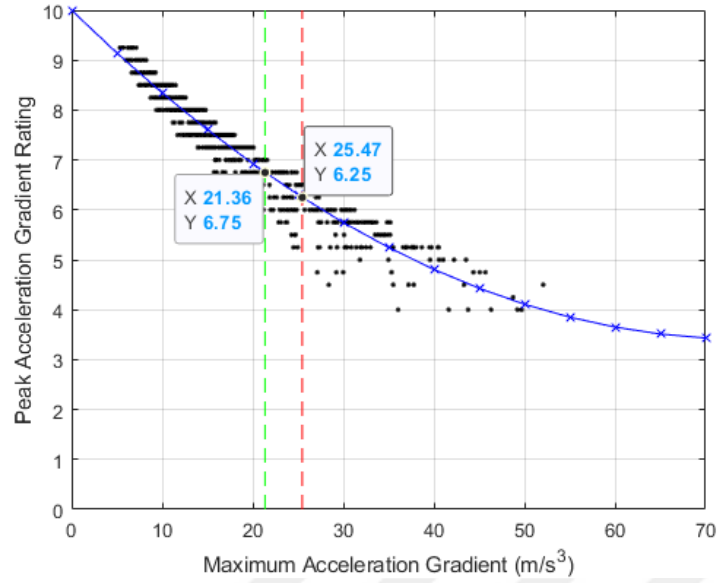


Figure 4.11: Peak acceleration gradient metric function.

Peak acceleration gradient metric is determined as maximum acceleration gradient has to be smaller than 21.36 m/s^2 based on the rating 6.75 on the trendline and as borderline acceptable level, it must not be above 25.47 m/s^2 which corresponds to rating 6.25.

Acceleration fluctuations metric function, given in equation (4.6), is obtained by fitting a power function to experts' evaluations results with respect to 1st acceleration oscillation parameter as shown in **Figure 4.12**.

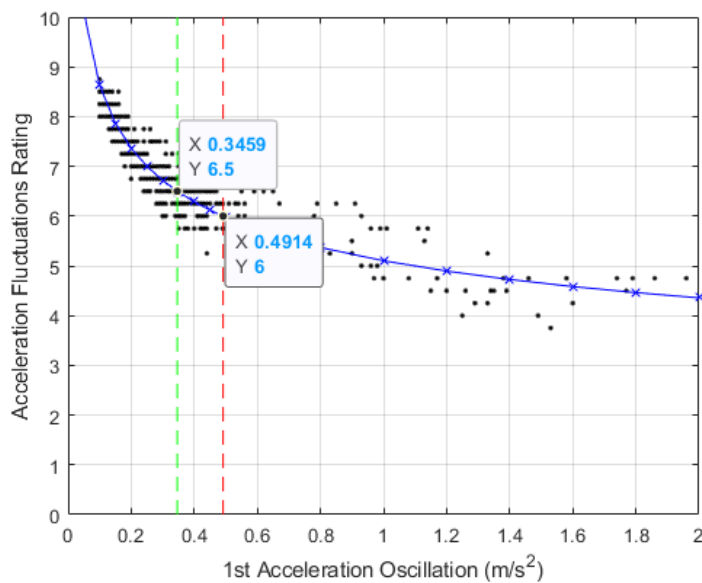


Figure 4.12: Acceleration fluctuations metric function.

$$5.1027 x^{-0.228}, 0.05 \leq x \leq 2.0 \quad (4.6)$$

Acceleration fluctuations metric is determined as first acceleration oscillation has to be smaller than 0.3459 m/s^2 where trendline crosses rating 6.5, and as borderline acceptable level, it must not be above 0.4914 m/s^2 based on the rating 6.0 on the trendline.

All metric functions' plots are combined and given in **Figure 4.13**.

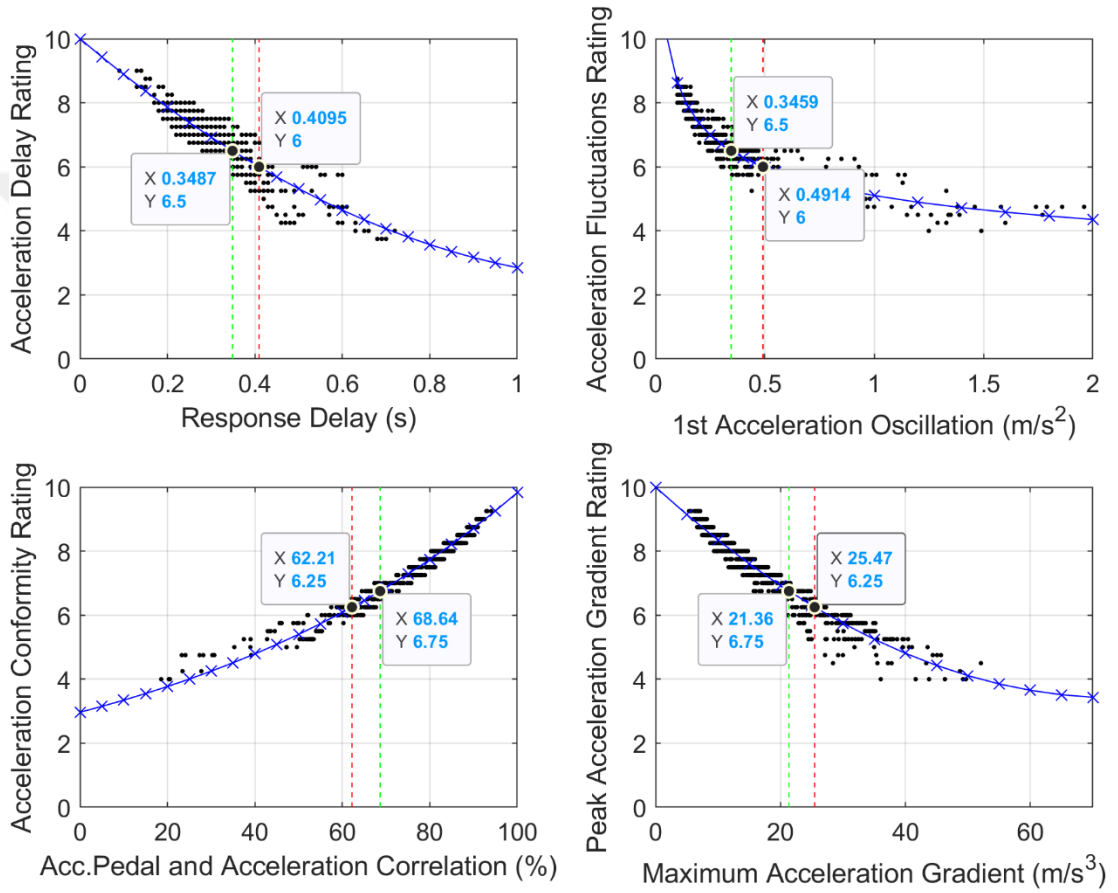


Figure 4.13: Criteria metric functions.

5. ONLINE OPTIMIZATION

In this chapter, online optimization studies are explained. For online optimization, tip-in cost function, criteria weight factors, and application interface are developed. Then, optimization algorithm and optimization parameter are determined. Finally, the proposed methodology is applied and validated in the vehicle and results are presented.

5.1 Tip-in Rating Function & Criteria Weight Factors

Tip-in rating function is formulated and used as cost function for optimization using the rating values of each criterion. Tip-in rating function is formulated as given in equation (5.1).

$$\sum_{i=1}^n cf_i cr_i w_i / w_T \quad (5.1)$$

in which cr_i is criterion rating, w_i criterion weight, w_T total weight and cf_i correction factor where i is denoted for number of criteria.

The formula contains weights for each criterion so they can have different effects on final tip-in rating. For small passenger and light commercial vehicles with manual transmission, criteria weights are selected as given in **Table 5.1**.

Table 5.1: Criteria weights.

Criterion	Weight
Peak Acceleration Gradient	2
Acceleration Fluctuations	1
Acceleration Delay	1
Acceleration Conformity	3

Acceleration conformity criterion is regarded as more important and its weight is set to a higher value compared to other criteria, and acceleration delay and acceleration fluctuations get lower weights than peak acceleration gradient criterion. For different type of vehicle and transmissions as well as different driving modes, criteria weights need to be studied and updated. For example, when performance is preferred over comfort performance criteria weights could be higher and drivability criteria weights might be less.

Additionally, even though weights for criteria are determined based on average driver expectations of selected vehicle type, calculation is not linear as low ratings need to have more effect on overall rating to reflect customer's actual perception, and this approach is realized in the rating function with correction factor cf_i which is a function of criterion rating.

For criterion rating above 7.0, correction factor value is set to 1.0, which means no correction for ratings above 7.0. Starting from rating 7.0 towards 1.0, correction factor is decreased exponentially where it is set to 0.0 at rating value of 1.0 as shown in **Figure 5.1**.

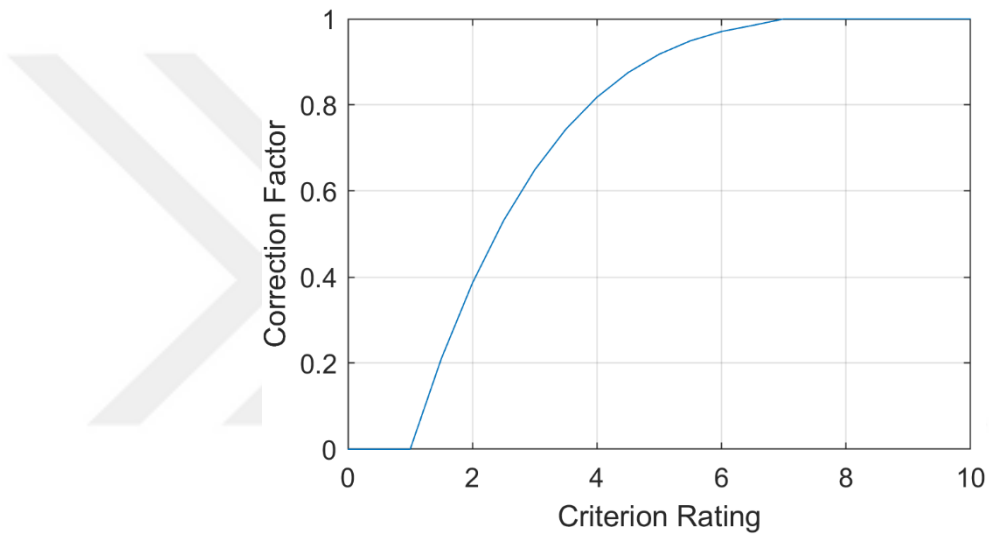


Figure 5.1: Criterion rating correction factor.

As a result, tip-in rating function can be used for overall tip-in maneuver objective assessment, combining both drivability and performance criteria.

5.2 Optimization Algorithm

For online optimization, golden section algorithm is selected. Golden section algorithm is a numerical optimization method used to find the lowest or highest value of a function in the range in which the optimum value is known to exist. The golden ratio is used in spacing of evaluation points, that is why this search algorithm is called golden section [Kiefer, 1953].

Starting with two evaluation points within the user defined interval, in each step upper or lower section is removed from search interval based on cost function value at the

evaluation points. After a section is removed, upper and lower bounds are redefined, and a new evaluation point is calculated in the new interval where the second one is already present and evaluated.

This way with every calculation and evaluation, interval is progressively reduced. Aim is to find optimum values of the parameters used in engine management software regarding cost function developed from performance and drivability criteria. When either user defined number of evaluation points or proximity of evaluation points conditions are satisfied, loop breaks, and optimization is completed. Golden section algorithm calculation steps are given in **Figure 5.2**.

L_l : lower limit, L_u : upper limit, gr : golden ratio $(\sqrt{5} - 1)/2$, t : tolerance, e_1 & e_2 : evaluation points
 in : iteration number, in_mx : maximum iteration number, $f(e_i)$: function result @ evaluation point e_i
 Step 1: Define L_l , L_u , t & in_mx
 Step 2: $e_1 = (1 - gr) * L_l + gr * L_u$, $e_2 = gr * L_l + (1 - gr) * L_u$, $in = 0$
 Step 3: $in = in + 1$
 If $f(e_1) > f(e_2)$
 $L_l = e_1$, $e_1 = e_2$
 $e_2 = gr * L_l + (1 - gr) * L_u$
 Else
 $L_l = e_2$, $e_2 = e_1$
 $e_1 = (1 - gr) * L_l + gr * L_u$
 Step 4: Repeat Step 3 until $in > in_mx$ or $|f(e_1) - f(e_2)| < t$

Figure 5.2: Golden section algorithm steps.

5.3 Optimization Parameter

During transient maneuvers, accelerator pedal and engine speed based maps for each gear and an additional instantaneous torque and gear based map are used for torque control. The instantaneous torque change rate is calculated by multiplying the outputs of these maps.

For optimization, a normalized torque rate curve based on instantaneous torque is defined. Other parameters used for the determination of torque rate, accelerator pedal and engine speed based maps for each gear, are kept constant, and a multiplier value that updates the torque rate curve is used as an optimization parameter.

In the normalized torque rate curve, the torque rate of change is reduced when approaching zero torque from negative torque. In order to prevent failure modes, the torque rate of change is kept low at zero torque region, and then the rate of change is

increased as the torque increases. Default shape of the curve is shown in **Figure 5.3** where the values are in the range between 0 and 1. The curve value is set to 0.5 at -50Nm breakpoint and set to 0.3 in in-lash region (± 10 Nm) and increased to 1 towards maximum torque value.

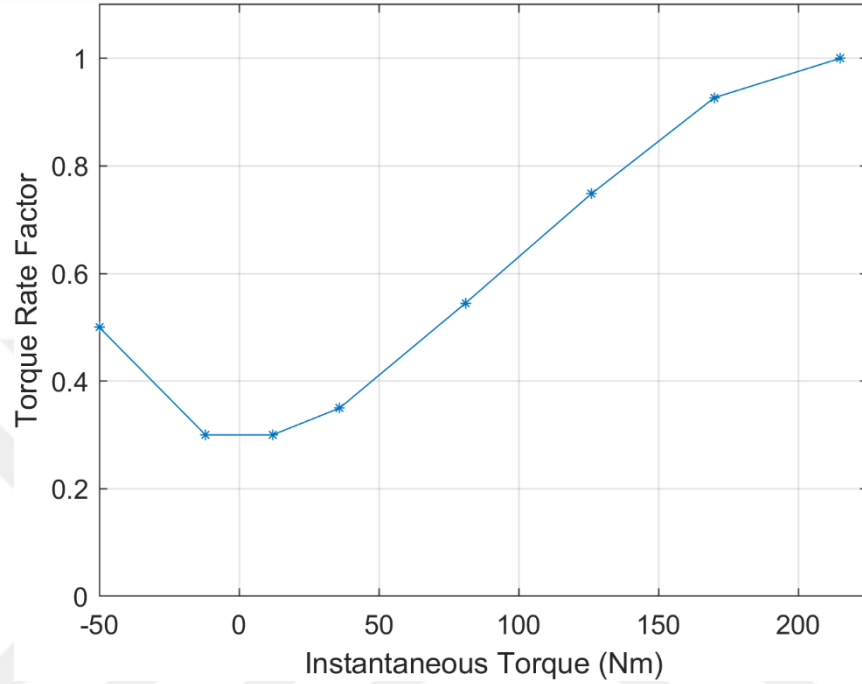


Figure 5.3: Default curve for torque rate.

After each gear, engine speed and accelerator pedal position point is optimized with the optimization parameter using the torque rate of change curve, accelerator pedal and engine speed based maps are reshaped using the optimum values determined for each gear and the updated calibration is downloaded to the engine control unit. In this way, optimum performance and driving comfort are ensured.

5.4 Application Interface

ATI Vision, which is a commercial tool, is used to take measurements from engine control module and the instrumentation.

To demonstrate effectiveness of the proposed method, a graphical user interface is developed in MATLAB and from this interface optimization is studied online on a test vehicle.

5.4.1 User Interface Settings

Graphical user interface uses ATI Vision application programming interface (API) to connect to engine control module and ATI Vision data recording and exporting features. Developed graphical user interface is shown in **Figure 5.4**.

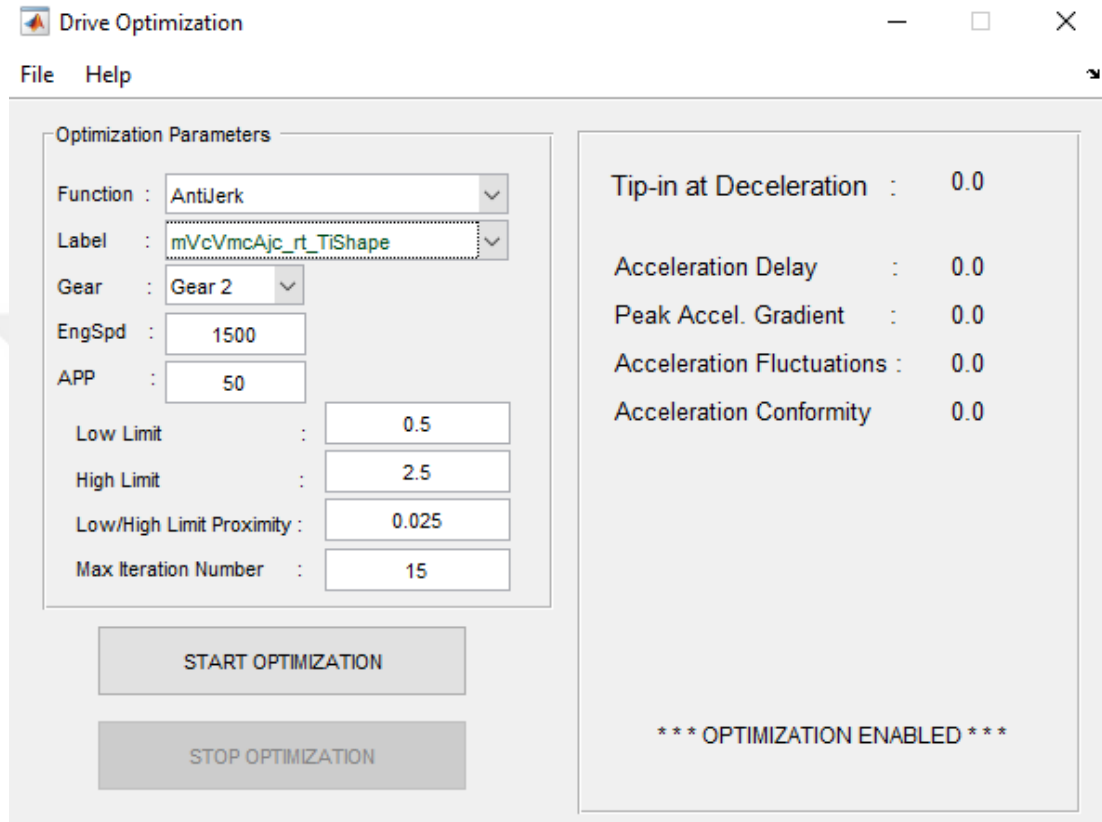


Figure 5.4: Graphical user interface.

Firstly, user defines optimization algorithm parameters before optimization can be started. From interface user can select function and related labels to be optimized and define constraints for these labels.

Additionally, from the interface user can set upper and lower parameter limits, and optimization exit conditions (iteration number and upper lower parameter value difference).

Second process before starting optimization is defining vehicle program and parameter files that contain characteristics of the vehicle, transmission, and engine. When “start optimization button” is pressed user is asked for vehicle program and parameter files.

After parameters are loaded, tool checks whether ATI Vision software is open and makes connection through its API. If connection is successful, criteria functions are loaded, and optimization is enabled.

When ECU and ATI Vision are connected, measurement channels in the ECU can be monitored. Measurement channels read for optimization from engine control unit via ATI Vision software is shown in **Figure 5.5**.

	Name	Units	Description
	APP_r	%	Standardized accelerator pedal position
	Brk_st	-	Brake switch state
	Clth_rClth	%	Clutch Pedal Position
	Epm_nEng	rpm	Average engine speed of one cylinder segment
	PthSet_trqlnrSet	Nm	PthSet: inner torque set value
	Tra_numGear	-	Current gear information
	VehV_v	km/h	Vehicle speed

Figure 5.5: Engine control unit measurement channels.

If optimization is enabled, either manually or automatically by checking whether weighted average of cost function values is below a pre-determined threshold for any operating point, optimization sequence is started, and tool arms recorder trigger conditions.

5.4.2 Recorder Configuration

Recording times, measurement channels, recorder start and stop trigger conditions, file name and file path and export file extension configurations are done via recorder properties screen in ATI Vision software.

Pre-trigger recording time is set to 1 second in order to contain event initial conditions. Post-start trigger recording time is set to 60 seconds, since recording starts from deceleration maneuver just before the tip-in event, and this duration needs to be long enough to capture tip-in event.

Recording start and stop trigger conditions are defined according to event detection algorithm described in section 3.4, so during driving when start trigger conditions are satisfied tool arms the recording to take required data from engine control unit.

Recorder properties screen is shown in **Figure 5.6**.

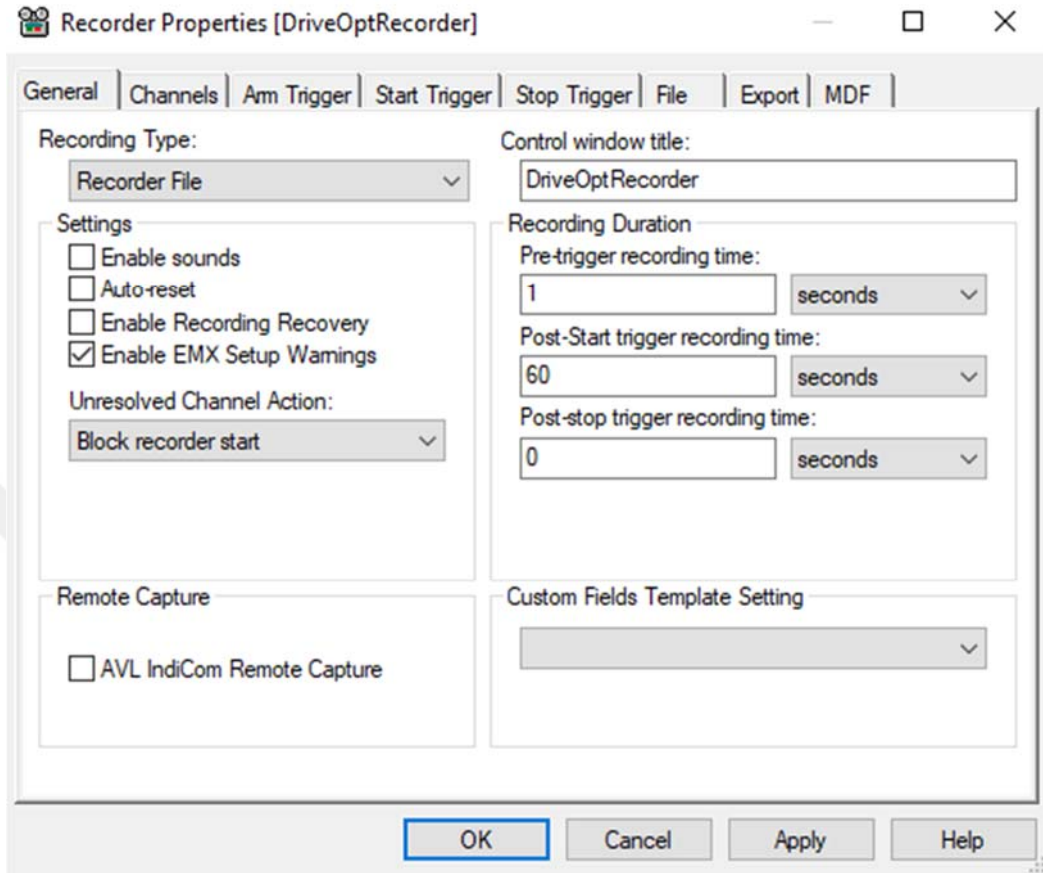


Figure 5.6: Recorder properties.

5.4.3 Optimization Sequence

When optimization is enabled for a specific test condition; gear, accelerator pedal position and engine speed; optimization parameter value is iteratively updated to optimize comfort and performance for that specific event.

When a new recording is exported to working directory, tool automatically analyzes the recording and calculates criteria and tip-in event ratings. After each recording analysis, tool automatically updates optimization parameter and arms start trigger condition to take another recording with updated parameter value.

Aim is to find optimum value of the parameter with regard to cost function developed from performance and drivability criteria. At every iteration optimization parameter value is chosen based on optimization algorithm and cost function value at the evaluation point, and this process is repeated until optimum result is reached.

When optimization is stopped or completed, criteria and tip-in rating results are exported to an excel file and a MATLAB data file, and if desired user can continue optimization later via importing result file before optimization.

Additionally, for safety some precautions are implemented such as in case of heavy braking or any error code set from on board diagnostics (OBD), optimization is stopped, and updated label values are set to their base values.

5.5 Model Verification and Optimization Results

Model verification and optimization is studied with a light commercial vehicle, Transit Courier by Ford Motor Company. The detailed vehicle specifications are listed in **Table 5.2**. The vehicle is installed with an accelerometer for high-resolution longitudinal acceleration. Other input signals are taken from engine control unit.

Table 5.2: Specifications of the test vehicle.

Description	Specification
Power pack	DV5
Model	Courier
Engine	1.5l DV5FD
Rated Horsepower (PS)	85 PS
Maximum Torque (Nm)	215Nm
Emission Level	Euro 6
Transmission	6 speed - 6MX65
Final Drive Ratio (FDR)	3.55
Curb Weight (kg)	1450kg
Tire Size	195/60R15

For validation, tests were performed in 2nd gear with various accelerator pedal inputs at 1500-2000 rpm engine speed range. For optimization, maximum number of evaluations is set to 15 and parameter proximity is set to 0.025. Lower and upper bounds are set to 0.5 and 2.5 respectively, as it is known that with 0.5 setting performance is poor and with 2.5 setting torque rate is very high and response is very harsh.

Tip-in and criteria ratings with respect to calibration multiplier values from 2nd gear at 1500 rpm engine speed and 50% accelerator pedal tests are given in **Figure 5.7**.

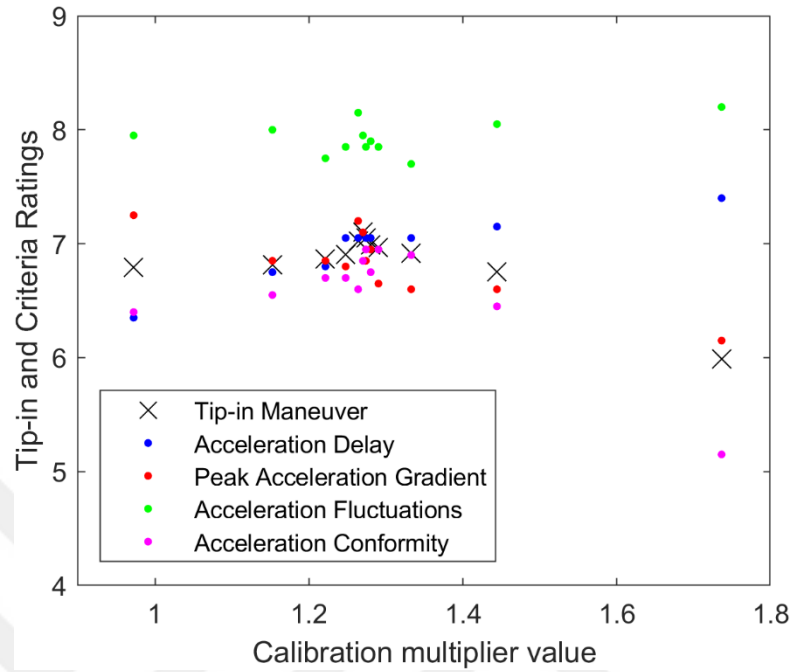


Figure 5.7: 2nd gear 1500rpm 50% pedal input, calibration multiplier values vs tip-in and criteria ratings.

Corresponding torque rates with respect to instantaneous torque for each calibration multiplier value are given in **Figure 5.8**.

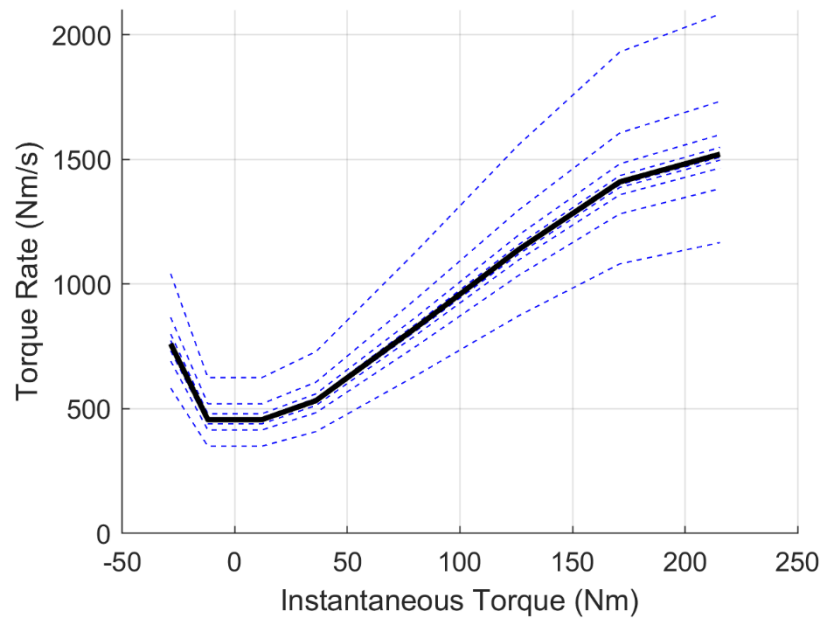


Figure 5.8: Instantaneous torque vs torque rate for each multiplier value.

From the results, with increasing calibration multiplier values performance is getting better; however, shuffle amplitudes are getting higher, and vice versa. Resultant optimum calibration multiplier value is 1.27 with less shuffle amplitudes; satisfied driving comfort, and acceptable performance with a rating of 7.1. Corresponding acceleration profiles are given in **Figure 5.9**.

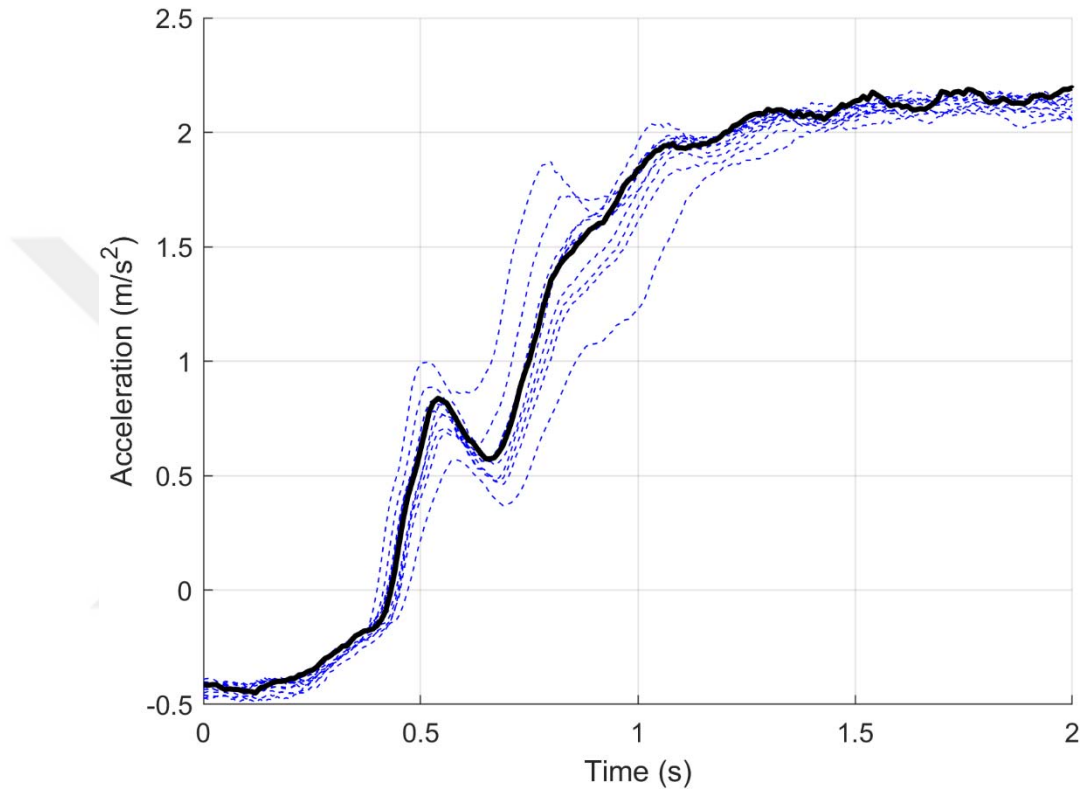


Figure 5.9: Acceleration profiles from 2nd gear 1500rpm engine speed and 50% accelerator pedal position optimization maneuvers.

Tests are also evaluated by the experts and almost all test results are within ± 0.1 rating range which represents the validity of the optimization process. As a result, optimization is performed with combined cost function developed for the evaluation of performance and drivability attributes, and proposed algorithm is proven to be effective for improving driving quality.

Test results are given in **Table 5.3**.

Table 5.3: Test results at 2nd gear 1500rpm 50% pedal position.

Calibration multiplier value	Calculation Results					Experts' Ratings			
	Tip-in Rating	Acceleration Delay	Peak Acceleration Gradient	Acceleration Fluctuations	Acceleration Conformity	Acceleration Delay	Peak Acceleration Gradient	Acceleration Fluctuations	Acceleration Conformity
1.264	7.02	7.05	7.20	8.15	6.60	7.00	7.25	8.25	6.50
1.736	5.99	7.40	6.15	8.20	5.15	7.50	6.00	8.25	5.25
0.972	6.79	6.35	7.25	7.95	6.40	6.50	7.25	8.00	6.50
1.444	6.75	7.15	6.60	8.05	6.45	7.25	6.50	8.00	6.50
1.152	6.82	6.75	6.85	8.00	6.55	6.75	7.00	8.00	6.50
1.333	6.92	7.05	6.60	7.70	6.90	7.00	6.50	7.75	7.00
1.221	6.87	6.80	6.85	7.75	6.70	6.75	6.75	7.75	6.75
1.290	6.97	6.95	6.65	7.85	6.95	7.00	6.50	7.75	7.00
1.248	6.91	7.05	6.80	7.85	6.70	7.00	6.75	7.75	6.50
1.274	7.05	7.05	6.85	7.85	6.95	7.00	6.75	7.75	7.00
1.280	6.99	7.05	6.95	7.90	6.75	7.00	6.75	8.00	6.75
1.270	7.10	7.10	7.10	7.95	6.85	7.00	7.00	7.75	6.75

Same methodology is applied to other accelerator pedal positions, engine speed and gears, and resultant look-up table is shown in **Figure 5.10**.

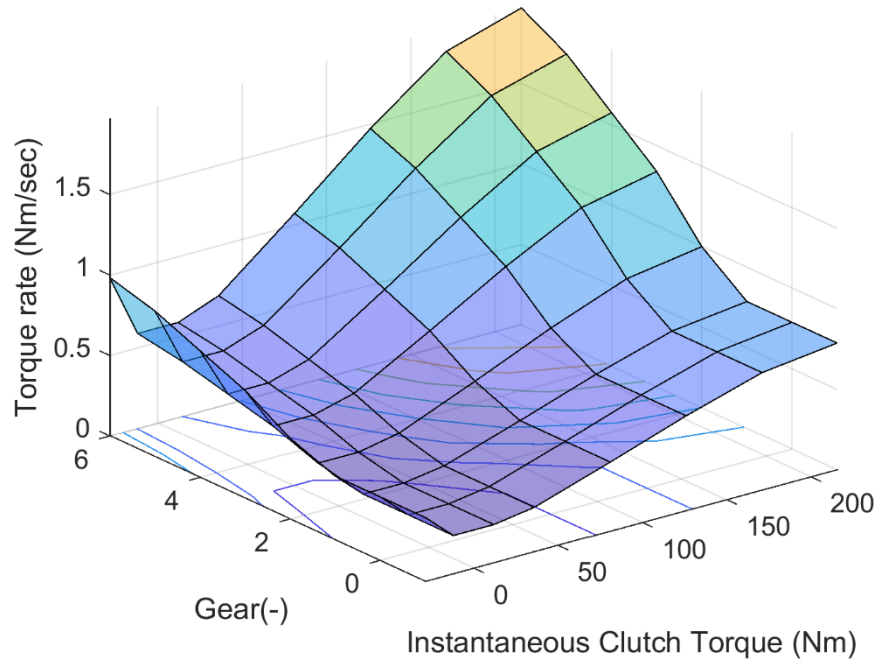


Figure 5.10: Torque rate map based on instantaneous torque and gear.

In torque control software there is another lookup table based on engine speed and accelerator pedal position as shown in **Figure 5.11**, and this table is also updated based on optimization results, and combined effect of these look-up tables are considered. As a result, in this table with increasing engine speed and accelerator pedal position, torque rate values are increasing since at higher pedal positions and engine speeds, performance is preferred over comfort as formulated in criteria rating functions.

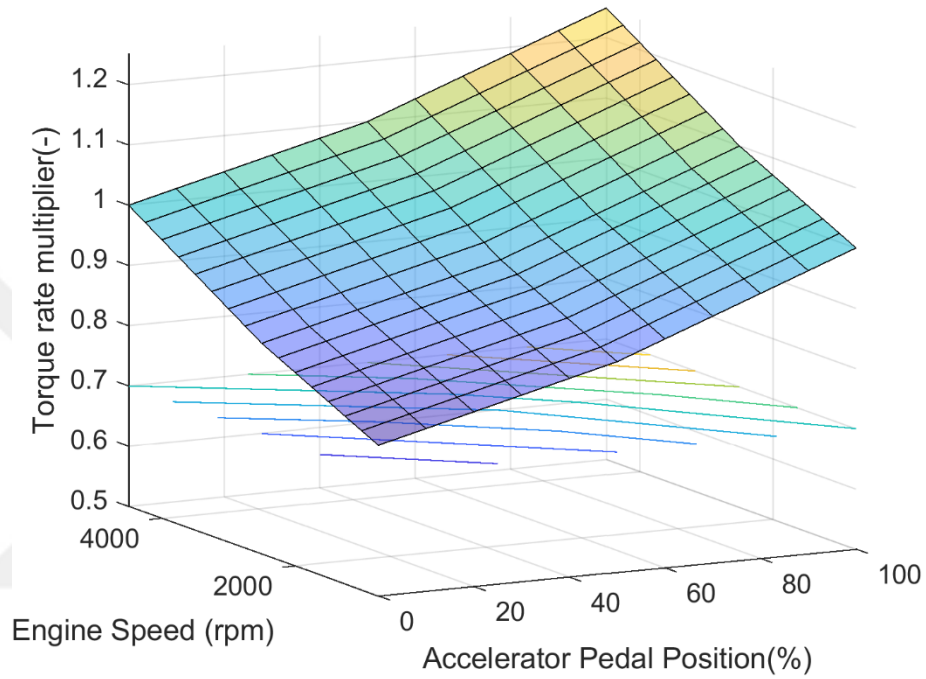


Figure 5.11: Torque rate multiplier map based on accelerator pedal position and engine speed.

6. VEHICLE MODEL

In this chapter, main motivation is to investigate the feasibility of utilizing a vehicle model to calibrate the lookup tables in the engine control unit using developed criteria and tip-in rating functions. To analyze performance and drivability attributes and demonstrate real vehicle behavior in simulation environment, a vehicle model is developed, and simulation results are compared with the test data. A model in the loop (MIL) simulation environment with a detailed vehicle model incorporated with a control algorithm could provide cost and time efficiency since it makes performing same maneuvers possible repeatedly without a need of a test vehicle once system parameters are identified. It could also provide capability to perform maneuvers in various test conditions, analyzing potential error states and effects of system parameters.

From the literature, it is verified that for a model to correctly represent an actual vehicle, it must include a backlash model and all the driveline elements which define characteristics of the driveline [Lagerberg and Egardt, 2007]. In this work, MATLAB Simulink – Simscape is used for elastic driveline model development. Vehicle model is developed for a front wheel drive (FWD) vehicle. Simplified driveline model for a FWD vehicle is shown in **Figure 6.1** [Oglieve et al., 2017].

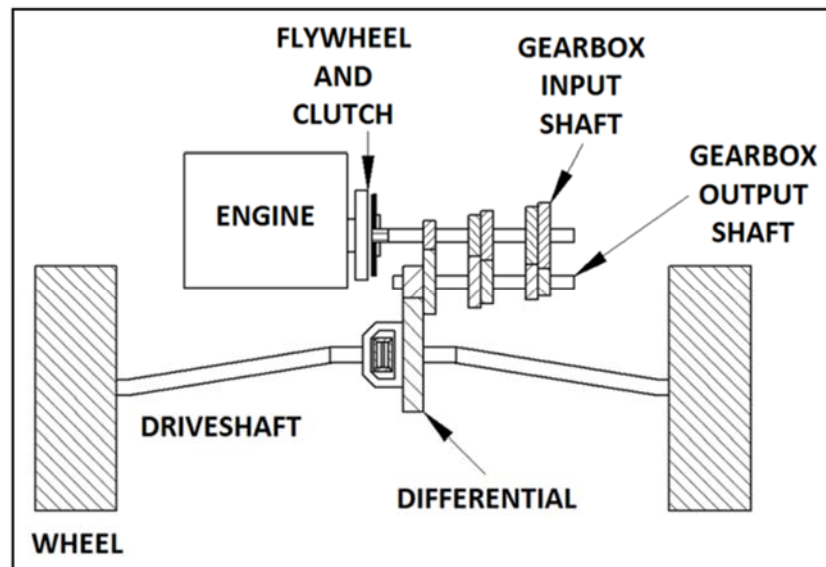


Figure 6.1: Simplified driveline model [Oglieve et al., 2017].

6.1 Vehicle and Driveline Model Development

Developed model consists of test setup and engine torque structure sub-models (pedal maps, limitation & protections, and anti-jerk model), as well as driveline components such as clutch, transmission, differential, backlash, half shafts, tires, and vehicle body. Among driveline components, clutch and half shafts are modelled as elastic components, and transmission and differential are assumed to be stiff.

Backlash between driveline elements is also modelled to demonstrate real vehicle behavior during tip-in maneuvers since backlash can cause error states during lash crossing. In the model, all backlash contributions within the powertrain are combined and represented in a single backlash component.

6.1.1 Test Setup Model

Test setup model consists of target engine speed for tip-in maneuver, target gear, test accelerator pedal position, accelerator pedal rate setting and final engine speed as a stop trigger condition. Targets are set from MATLAB workspace via parameter loading script.

To achieve a tip-in event at the target engine speed, an initial engine speed that surpasses the target engine speed is set. This way simulation starts with deceleration section and when engine speed reaches target engine speed, accelerator pedal position is set to test pedal position with defined pedal rate. When engine speed reaches final engine speed, flip-flop block in the model is reset and accelerator pedal position is set to 0%. Test setup model is given in **Figure 6.2**.

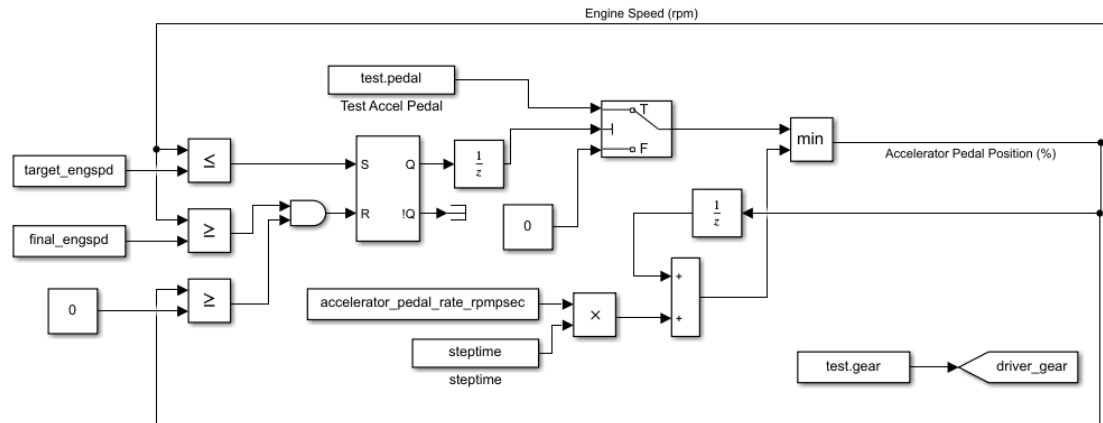


Figure 6.2: Test setup model.

6.1.2 Driver Torque Demand Model

Driver demand and torque arbitration model consists of pedal maps, gearbox limitations, full load torque curve and engine friction curve. Pedal maps are look-up table that outputs desired driver demand torque based on selected gear, accelerator pedal position and engine speed. In the model, the first step involves the computation of the minimum output obtained from the pedal map, gear-based torque limitation, and full load torque curve. Subsequently, the model generates an output signal by selecting the maximum value between the calculated minimum signal and the engine friction curve. This arbitrated driver demand torque is given as input to anti-jerk model.

Driver torque demand model is shown in **Figure 6.3**.

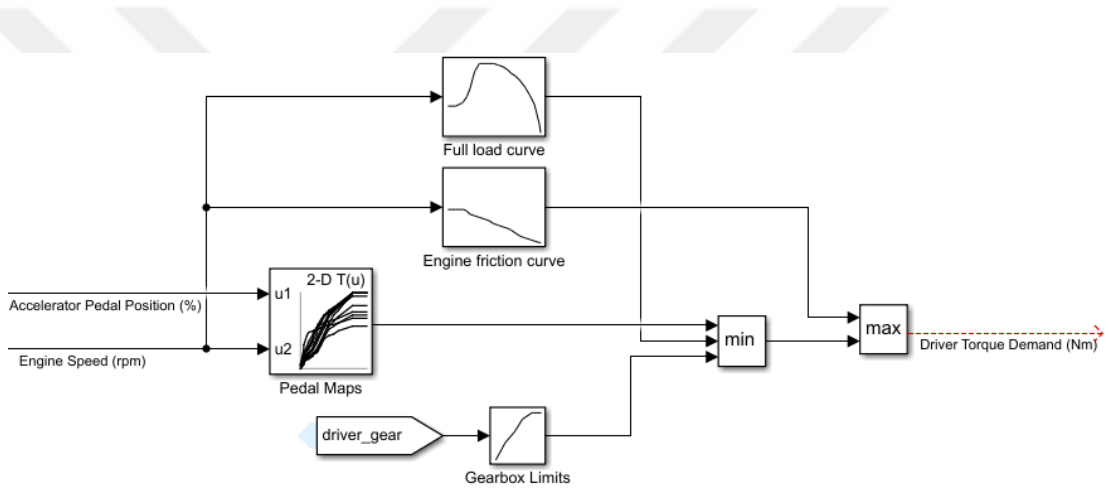


Figure 6.3: Driver torque demand model.

6.1.3 Anti-jerk Model

Anti-jerk model shapes driver torque demand based on selected gear and instantaneous clutch torque. Achieving optimal torque rise and decrease rates is crucial for a driveline to smoothly transition through backlash from negative to positive torque and vice versa, in order to prevent the occurrence of error states, including oscillations and sag, while also minimizing hesitation.

Anti-jerk model in engine management software is simplified but core functionality is preserved and integrated to vehicle model. There is a switch that enables this functionality. If it is active, when accelerator pedal is pressed, starting from the last arbitrated torque value calculated in driver torque demand block, output torque

increase is limited with a torque rate calculated from a gear and instantaneous torque based look-up table until driver demand torque is achieved. Additionally, to ensure the driveline can successfully pass through the backlash region while reducing the duration spent, a minimum allowed torque rate value serves as the lower limit threshold. Anti-jerk model is shown in **Figure 6.4**.

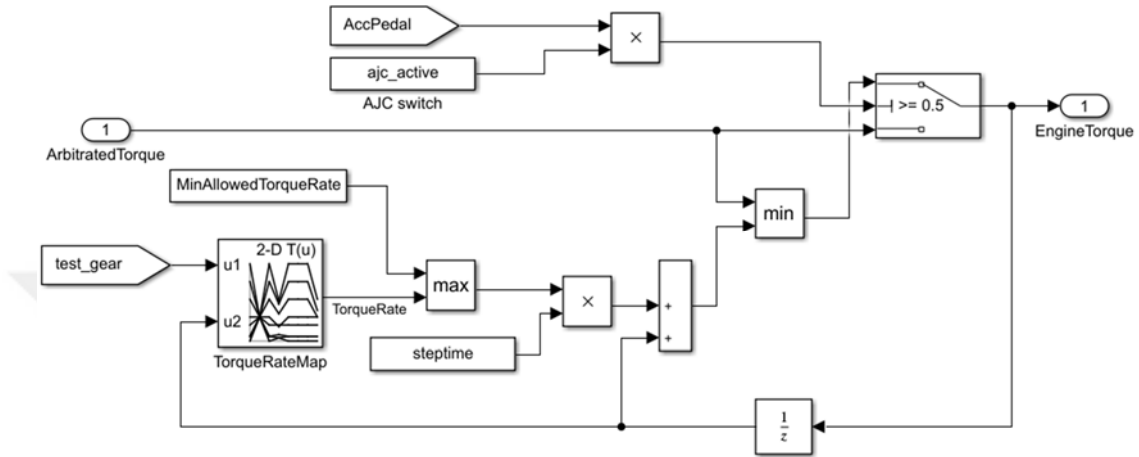


Figure 6.4: Anti-jerk model.

The integration of the anti-jerk model with developed elastic driveline model enables the investigation of the proposed optimization algorithm in simulation environment.

6.1.4 Driveline Model

Driveline model consists of clutch, transmission, differential, backlash, half shafts, tires and vehicle body. Anti-jerk model torque output is given as an input to driveline model. For driveline model, MATLAB/Simulink/Simscape is used. Simscape enables creating models of physical systems within the Simulink environment [Web 6, 2024].

Engine is modelled as a torque source element, and engine mechanics is characterized by an overall inertia that includes the contributions of the connecting rods, pistons, valve train system, crankshaft, and flywheel. Engine model output is engine speed and torque transmitted to clutch.

The clutch is modelled as a spring damper system. In this study, in gear tip-in maneuvers are studied; therefore, there is no open state in the clutch model. Clutch disc and pressure plate inertias are also included in the model. Clutch model output is torque transferred through clutch springs which is also transmission model input.

Transmission and differential are modelled as torque and speed transition elements, and half-shafts are modelled as spring damper element. In transmission model, gear ratio is defined based on engaged gear. Transmission output is output shaft angle and speed, and these outputs are input to the differential sub-model.

Developed vehicle model does not include propeller shaft since the transmission and differential is coupled in front wheel drive vehicles. Differential is modelled as torque and speed transition element. Model output is differential angle and speed.

Total backlash in all driveline elements is considered as a single backlash and modelled between differential and half shafts. Torque transfer is possible after backlash is passed, and contact is made to half shafts. Half shafts are modelled as torsional spring and damper element, and its output is torque transferred to wheels.

Friction parameterized model is used for tires and road friction is calculated in this block. Losses are subtracted from input torque, and model output is passed to vehicle model.

In vehicle model, road loads; road incline and aerodynamic drag, are calculated, and these losses are subtracted from output of tire model and traction force is calculated. As a result, acceleration is calculated from traction force and vehicle speed is calculated from acceleration signal.

Developed vehicle and driveline model is given in **Figure 6.5**.

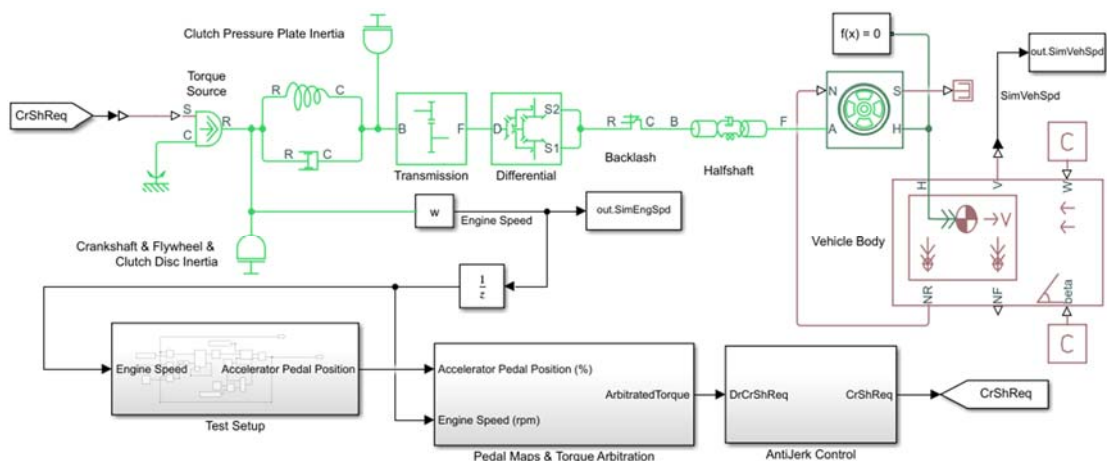


Figure 6.5: Vehicle and driveline model.

6.2 Test Procedures

Test vehicle is instrumented, and data is taken for model validation. Following test procedures are prepared for system identification.

1. Coast down (neutral and in-gear deceleration) maneuvers
2. Driveline characterization (tip-in and tip-out maneuvers)
3. Full load and stabilized accelerations

6.2.1 Coast Down Maneuvers

In order to obtain aero drag and road friction coefficients, neutral coast down maneuvers were performed. First, vehicle is loaded to performance test weight (PTW) which is unladen weight of the vehicle and 175 kg payload (1 driver, 1 passenger and half full of fuel tank) for small passenger and light commercial vehicles. Then neutral coast down maneuvers from around 120kph to 15kph vehicle speed on flat road are performed. Accelerator pedal is released, and all accessories are turned off during testing. For event detection, clutch and accelerator pedals are used; at the beginning of each maneuver, clutch pedal is released 0.5 sec after shift to neutral and at the end accelerator pedal is pressed, and data in between these trigger conditions are analyzed.

Neutral coast down maneuvers performed with a test vehicle are shown in **Figure 6.6**.

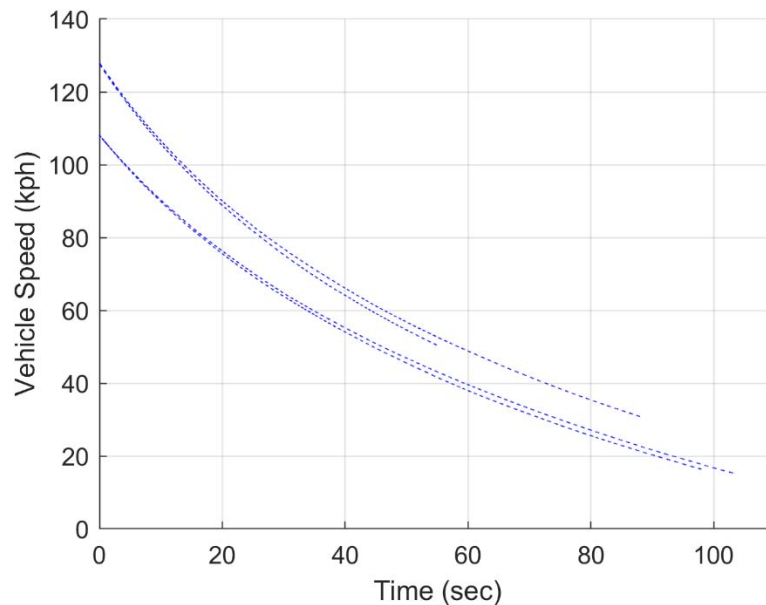


Figure 6.6: Neutral coast down maneuvers.

Same number of maneuvers are performed in each direction, and average of coast down gate times are recorded. Aero drag and road friction coefficient values are obtained from recorded gate times.

Similarly, in-gear coast down (deceleration) maneuvers are performed for combined engine and driveline losses, and road load validation. The procedure of executing in-gear coast down maneuvers involves initiating the process at an engine speed of 4500rpm (while adhering to the vehicle speed limit) and continue testing until the engine speed descends to a point below 1500rpm.

In order to show the deceleration in different gears comparatively, the deceleration profiles starting from the same engine speeds are shown in **Figure 6.7**.

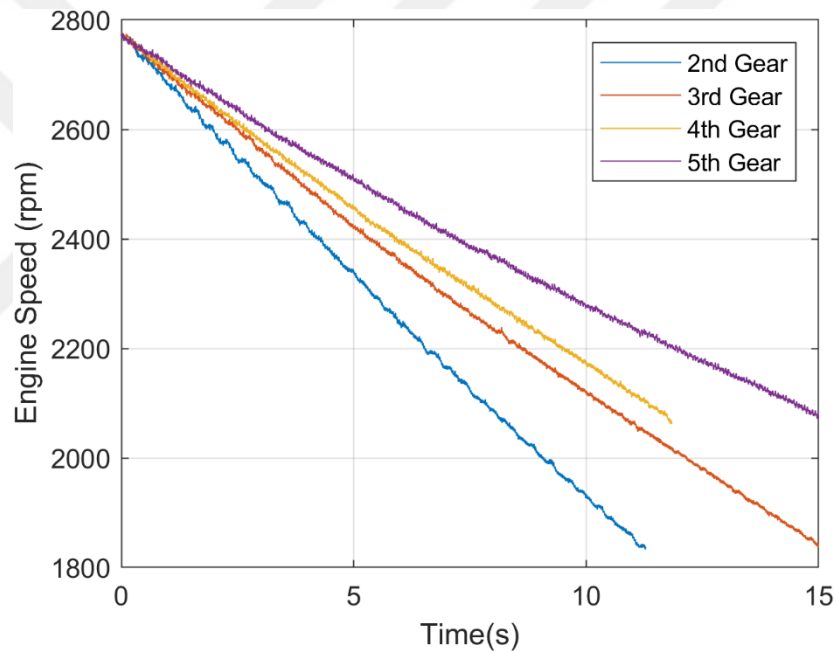


Figure 6.7: In-gear coast down maneuvers.

6.2.2 Driveline Characterization

For driveline characterization, apart from smoke limitation feature, all filters and limitations on torque path are disabled, and consecutive tip-in and tip-out maneuvers are performed. Smoke limitation function in engine management software is required to limit fuel quantity based on mass air flow into the engine, and this feature is not disabled. Disabling this feature would yield inaccurate torque values and lead to

incomplete combustion and black smoke because of excessive fuel injection for current mass air flow.

At first in each gear %20/%30/%40/%60/%100 pedal accelerations are performed from idle speed until engine speed reaches maximum possible or test speed limit (i.e. 4000rpm) and maximum engine speed values are recorded. Then, for each gear and pedal positions, speed intervals are selected according to engine speed increase rates.

For example, in 1st, 2nd and 3rd gears, 20% & 40% accelerator pedal inputs; tip-in and tip-out maneuvers are performed consecutively with +500rpm increase with tip-in maneuvers and -250rpm decrease with tip-out maneuvers until maximum engine speed is reached. For higher accelerator pedal inputs (60% & 100%), higher engine speed intervals are used.

During maneuvers, accelerator pedal positions are kept for at least 3 seconds or until necessary engine speed increase is obtained.

After each tip-in/out maneuver, engine speed shuffle periods are recorded, and driveline natural frequencies are calculated from shuffle periods. The engine speed profiles observed during powertrain characterization tests are shown in **Figure 6.8**.

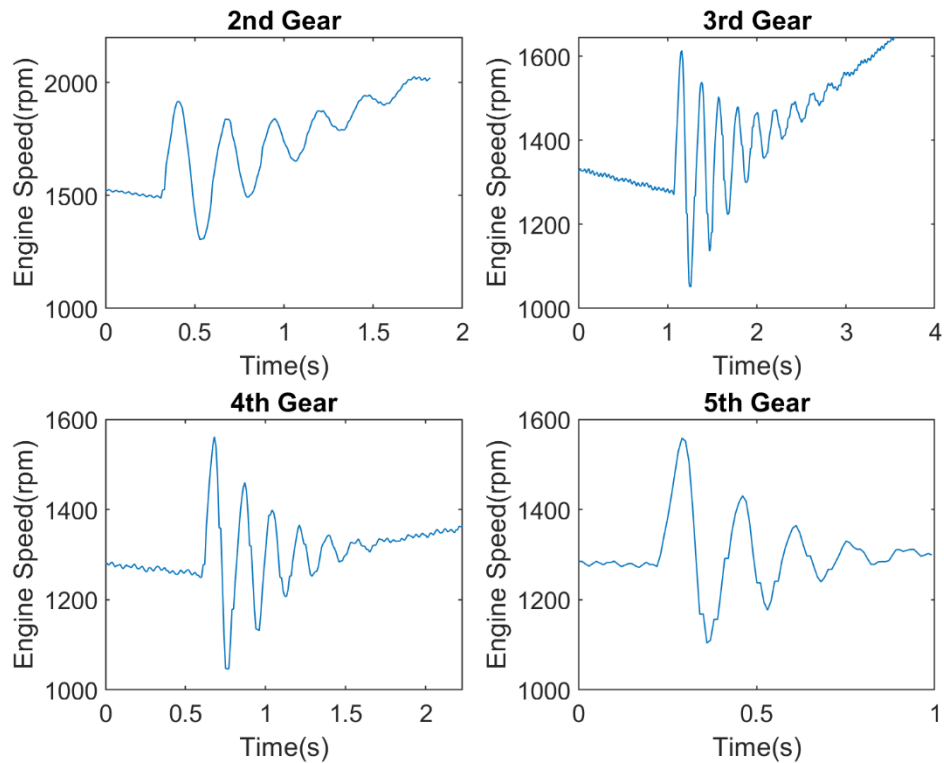


Figure 6.8: Driveline characterization engine speed profiles.

From the analysis, driveline natural frequencies are 3.72Hz, 4.45Hz, 5.9Hz and 6.25Hz for 2nd, 3rd, 4th, and 5th gears respectively.

6.2.3 Full Load and Stabilized Accelerations

Full load and part load stabilized acceleration tests are performed for engine and driveline inertia determination.

For full load tests, first engine speed is accelerated to 1250 rpm and accelerator pedal is released. Then during deceleration from just above idle speed setpoint (~1000rpm) vehicle is accelerated with wide open throttle (WOT) until engine speed reaches engine speed limit or maximum possible vehicle speed due to speed restrictions. First 3 seconds of these maneuvers are categorized as tip-in maneuvers and after oscillations are damped, remaining acceleration sections are categorized as stabilized accelerations.

Engine speed profiles of full load stabilized accelerations are shown in **Figure 6.9**.

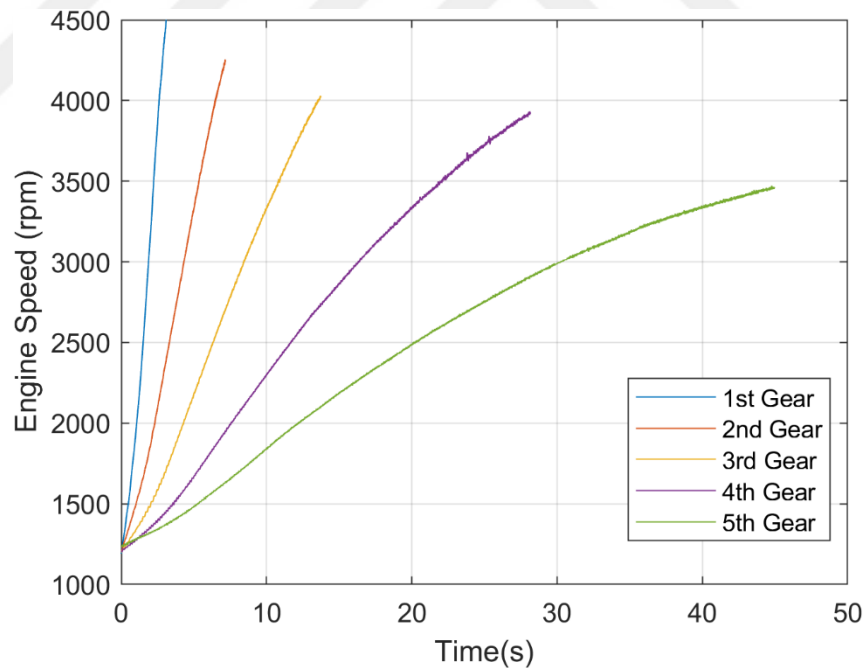


Figure 6.9: Engine speed profiles of stabilized accelerations.

6.3 System Identification

In order to obtain the parameters of the components in the driveline and vehicle model, neutral coast down, in-gear coast down (deceleration), stabilized accelerations, tip-in and tip-out maneuvers are performed in the test vehicle. Data gathered from the vehicle is used for parameter tuning.

Firstly, the aero drag coefficient and road friction coefficient values are determined via neutral coast down maneuvers. Road load (F_{rl}) is modelled as the sum of the aerodynamic drag (F_{aero}), rolling resistance (F_{rr}) and road gradient term (F_g) as given in equation (6.1). Vehicle weight (m_{tot}), frontal area (FA), air density (ρ_{air}), vehicle velocity (v), gravitational acceleration (g) and road inclination (α) information is available, and using road load formulation, aero drag coefficient (C_d) and road friction coefficient (fr) are found.

$$F_{rl} = F_{aero} + F_{rr} + F_g \quad (6.1)$$

where

$$F_{aero} = \frac{1}{2} * C_d * FA * \rho_{air} * v^2 \quad (6.2)$$

$$F_{rr} = m_{tot} * g * \cos(\alpha) * fr \quad (6.3)$$

$$F_g = m_{tot} * g * \sin(\alpha) \quad (6.4)$$

Neutral coast down maneuvers were performed in each direction on a flat road. Velocity step is set to 10kph, and deceleration times (gate times) are calculated and from the average of each gate time wheel force is obtained. Then wheel force results are fitted to a 2nd order polynomial, and aero drag and road friction coefficients are calculated from the equations (6.2) and (6.3). Equation (6.4) is not used since maneuvers are performed on a flat road so road inclination is zero. Calculation steps are given in **Figure 6.10**.

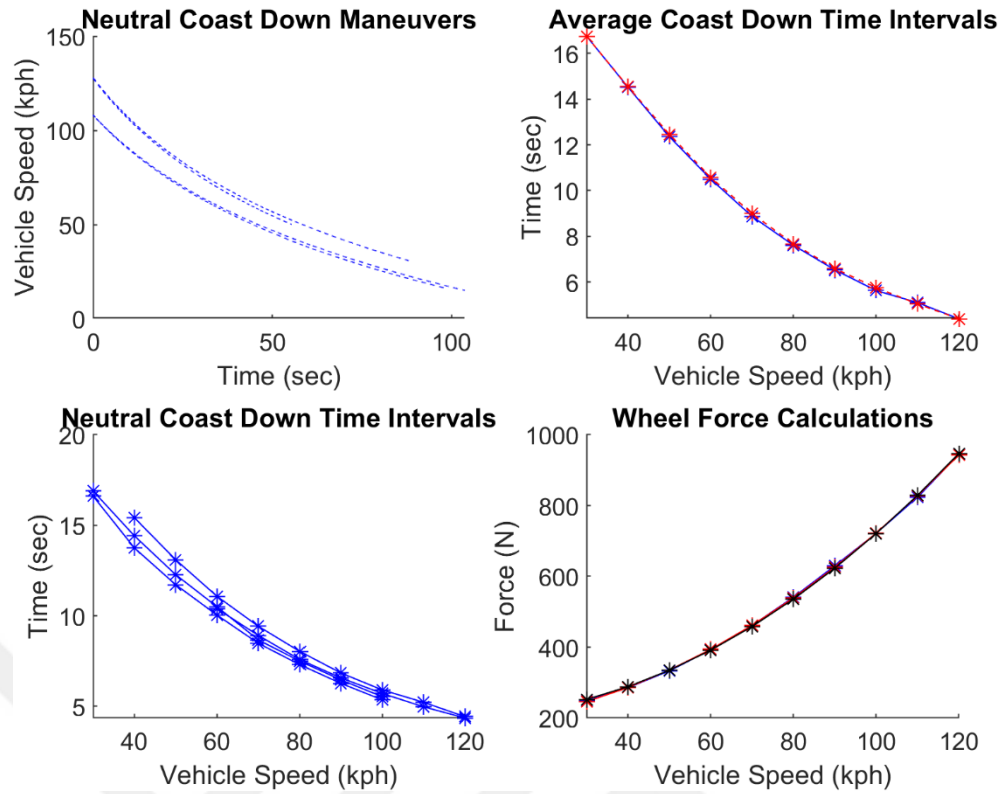


Figure 6.10: Neutral coast down analysis.

For system identification of the driveline, MATLAB optimization toolbox/response optimization/signal tracking feature is used.

Driveline model parameters are given in **Table 6.1**.

Table 6.1: Driveline model parameters.

Crankshaft, flywheel, and clutch inertias
Clutch damping coefficient
Clutch spring stiffness
Transmission efficiency
Driveshaft torsional inertia
Driveshaft torsional stiffness
Driveshaft damping ratio
Backlash size
Backlash contact stiffness
Backlash contact damping
Wheel inertia

For driveline components, in order to perform parameter tuning with signal tracking feature, torque demand section of the model is updated so that instead of modelled torque, recorded clutch torque data from test vehicle is used. By this means driveline parameters could be identified using vehicle test data.

Inertia and efficiency parameters are optimized to match test data with the simulations using in-gear coast down and stabilized acceleration maneuvers.

Maneuvers are performed in all gears and parameters are tuned based on vehicle speed and engine speed measurements. As an example, model responses of response optimizer using second gear coast down data are shown in **Figure 6.11**.

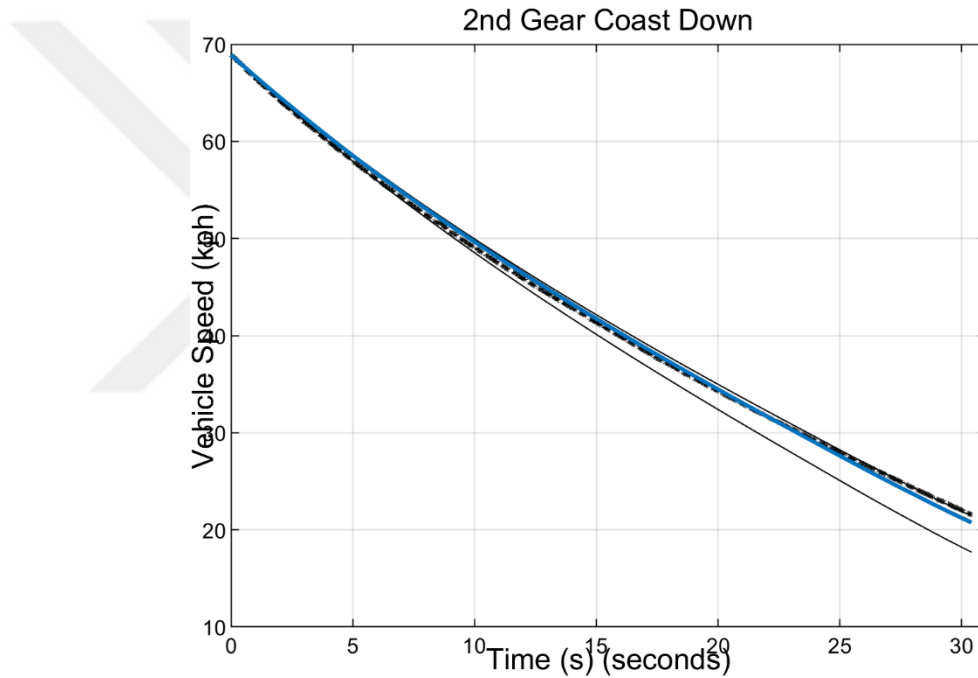


Figure 6.11: Parameter tuning with in-gear coast down maneuvers.

Additionally, stabilized acceleration measurement and simulation results comparison in second gear before and after parameter tuning are given in **Figure 6.12**.

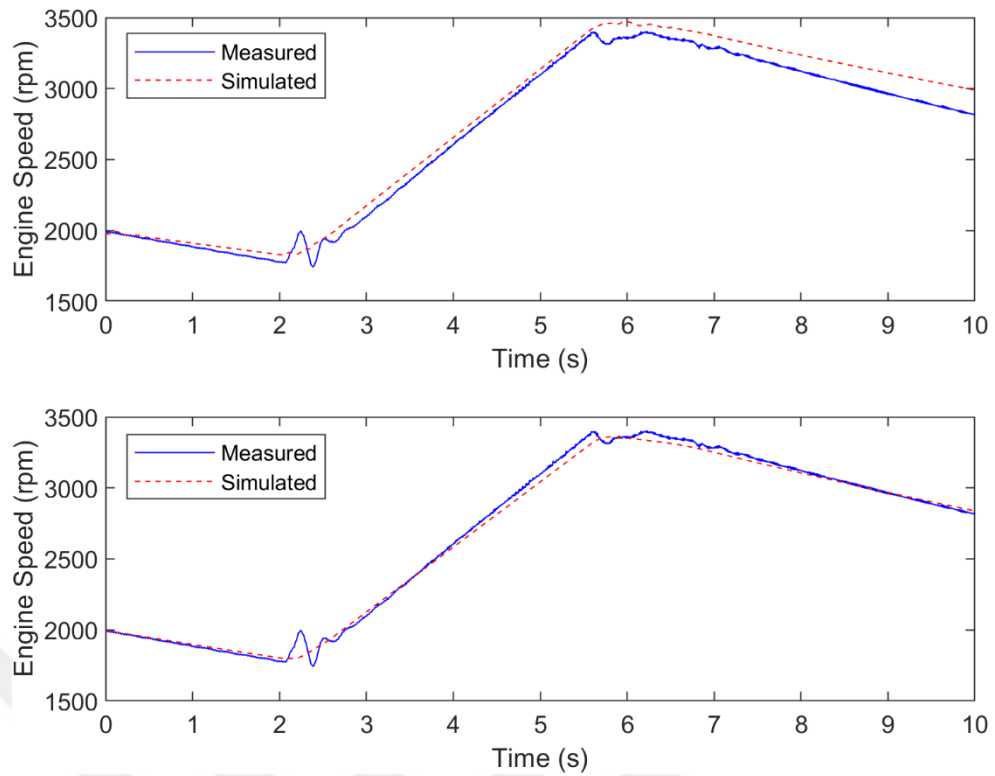


Figure 6.12: Parameter tuning with acceleration maneuvers.

After inertia and efficiency parameters are tuned, stiffness and damping parameters are optimized using vehicle test data gathered during tip-in maneuvers as shown in **Figure 6.13**.

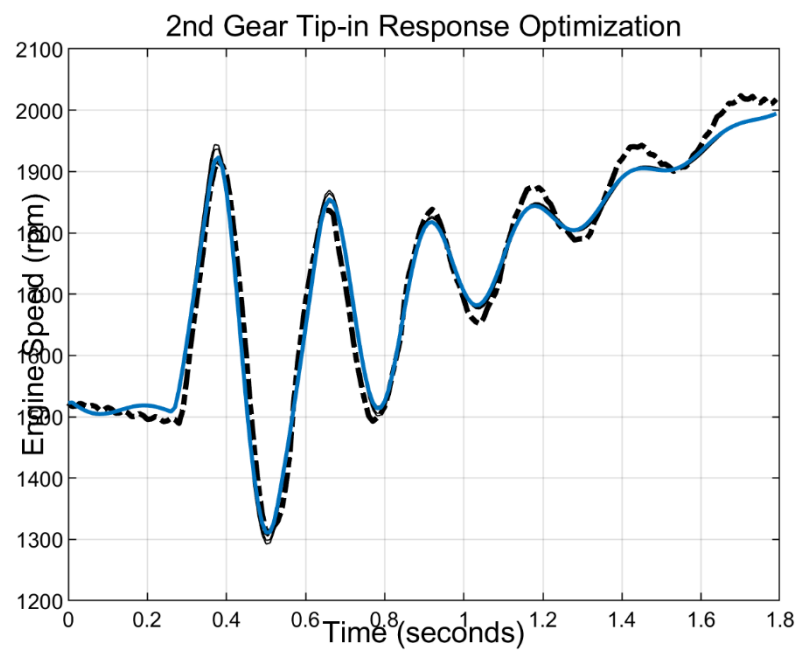


Figure 6.13: Parameter tuning with tip-in maneuvers.

During parameter tuning, it is observed that model is more sensitive to crankshaft, flywheel and clutch inertias, clutch spring stiffness, half shaft stiffness and backlash parameters compared to other parameters. These parameters have significant effect on oscillation magnitudes, frequency, and number of oscillations. Therefore, it is advised that these parameters should be considered during hardware selection.

Driveline model parameters are given in **Table 6.2**.

Table 6.2: Vehicle and driveline model parameters' values.

Parameter	Value	Unit
Total crankshaft, flywheel, and clutch inertia	0.4	kg.m ²
Clutch damping coefficient	0.25	Nm/(rad/s)
Clutch spring stiffness	10000	Nm/rad
Final Drive Ratio	3.5	—
Backlash size	0.1	rad
Backlash contact stiffness	30000	Nm/rad
Backlash contact damping	25	Nm/(rad/s)
Driveshaft torsional stiffness	25000	Nm/rad
Driveshaft damping ratio	0.48	—
Wheel inertia	1	kgm ²
Wheel radius	0.31	m
Road friction coefficient	0.015	—
Air Density	1.25	kg/m ³
Aerodynamic drag coefficient	0.45	—
Frontal area projection	2.5	m ²

In the table, values are rounded to give an approximate indication of the magnitudes of the values.

6.4 Simulation Results

After parameter tuning is completed, tip-in maneuvers are simulated, and the proposed optimization methodology is applied in the model environment to calibrate torque rate map for optimum driving comfort and performance.

Comparison of simulation and vehicle test optimization results for 2nd gear 50% accelerator pedal position at 1500 rpm engine speed tip-in maneuvers are shown in **Figure 6.14**.

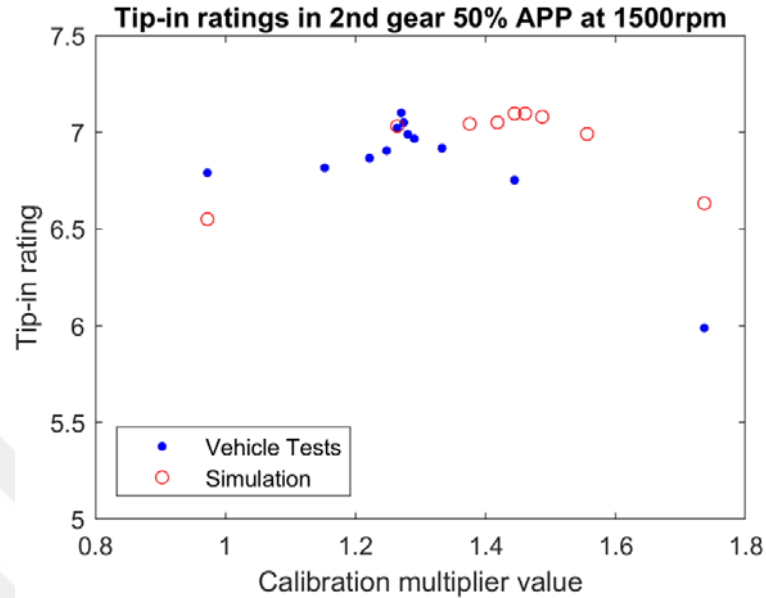


Figure 6.14: Simulation vs vehicle test optimization results for 2nd gear 50% APP at 1500rpm tip-in maneuvers.

Simulation results are not identical to actual test vehicle results. In simulations, calibration multiplier value is around 1.45 for optimum drivability and performance with a rating of 7.1; however, in vehicle tests, optimum calibration multiplier value was around 1.25.

When test vehicle measurements and simulation signals are compared, it is observed that clutch torque signals are not similar since engine is modelled as torque source in the vehicle model; however, the transient torque response of a diesel engine varies from its steady state torque response because of the inertial characteristics of airpath components such as the throttle valve, exhaust gas recirculation (EGR) valve, and turbocharger. In engine management software, despite sending the requested torque without any delays or filtering to the airpath control for a quicker response, there is still a delay in boost pressure buildup, known as boost lag, resulting in a torque reporting error during transient maneuvers.

Moreover, due to limited mass air flow initially during tip-in maneuvers, smoke limitation function limits torque to prevent black smoke. In simulation only active filtering and limitation function is anti-jerk control.

Therefore, even though driveline characteristics are similar, due to major differences in input torque signals, response delay, oscillation amplitudes and jerks are not identical and cause differences in criteria and tip-in function ratings.

Tip-in maneuvers in different gears, engine speed and accelerator pedal positions are simulated as well, and similar results are obtained. Therefore, it is concluded that with a simplified vehicle model, effect of optimization parameter can be studied; however, it is not enough to directly use optimized multiplier values via simulation for engine calibration. Results can only be used as a starting point for calibration studies.

Additionally, correlation between calibration multiplier value and criteria ratings are investigated in the simulation environment and results are shown in **Figure 6.15**.

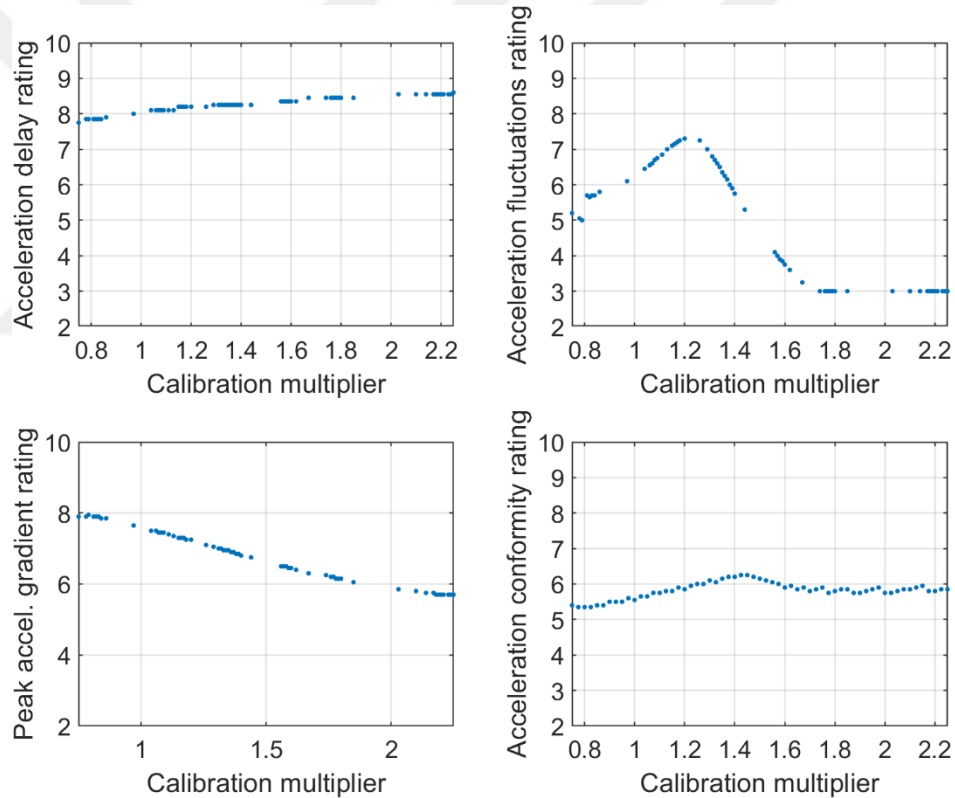


Figure 6.15: Calibration multiplier values vs criteria ratings.

With increasing calibration multiplier values, acceleration delay ratings are getting higher and peak acceleration gradient ratings decrease as expected. Moreover, with calibration multiplier values between 1 and 1.5, acceleration fluctuations and acceleration conformity criteria ratings are around optimum range and with multiplier values below 1 and above 1.5, their ratings decrease.

The simulation results are not the same as the vehicle test results; however, the trends are similar which shows that vehicle model can be used for calibration of torque control look-up maps and can reduce development time. However, fine tuning is still required via calibration engineers in the test vehicles.



7. CONCLUSION

Performance and drivability attributes are critical for customer satisfaction. Optimization of these attributes requires expertise and time, and mainly subjective assessment is used for signoff. Moreover, the drivability and performance attributes deteriorate over time due to mechanical wear and aging, which varies depending on the distance and conditions of use, and initial set of variables do not meet customer expectations in time and consequently optimization has also become necessary after the production. Unfortunately, the existing software structure cannot detect variations in system operation or adjust accordingly. Therefore, objective vehicle evaluation and online parameter optimization are some of the challenges in the field. This dissertation focuses on software development for drivability and performance evaluation and optimization. In this study, evaluation criteria are determined for performance and drivability attributes, rating functions for each criterion are formulated and combined cost function is developed. Then, a self-tuning algorithm is proposed to update lookup tables used in engine management software in real-time with feasible computational load and memory.

This dissertation consists of 5 main sections. In chapter 2, tip-in maneuver is determined for performance and drivability evaluations, torque control structure is analyzed, and assessment criteria are defined. Combined performance and drivability evaluation is important to comprehend driver perception of the vehicle's driving quality. However, assessments are done subjectively due to lack of objective metrics; therefore, as a first step after maneuver selection and torque control structure study objective assessment criteria are determined. One of the major contributions of this dissertation is evaluation criteria determination for performance and drivability attributes. In chapter 3, evaluation rating scale, design of experiments, and data acquisition and processing steps are explained. In chapter 4, objective measurements and subjective assessments correlation is investigated using response surface methodology, and rating functions and metrics for each criterion is formulated and combined cost function is developed. In chapter 5, online optimization using golden section algorithm is performed. Based on developed cost function, online optimization is performed and proposed methodology is proven to be successful for drivability and performance optimization.

The proposed adaptive online optimization methodology can replace or can be combined with subjective evaluations and methodology can be applied by any test engineer or researcher without any expertise on performance and drivability attributes.

Implementing such algorithm in powertrain control module is possible without significant memory and processing requirements. Software structure can be updated with addition of golden section algorithm, rating calculations from criteria functions and additional maps for score tables for each gear with accelerator pedal position and engine speed breakpoints in order to decide whether optimization is required. Additionally, most of the signals used for the calculations are already available in the software and remaining parameters can be added with ease.

The proposed software structure can be also used for diagnostics purposes, as the algorithm enables tracking system operation and avoid system failures. Additionally, during production phase, this approach minimizes the vehicle testing; therefore, reducing the testing time and development costs of the overall calibration process.

Additionally, in chapter 6, it is investigated whether a vehicle model could be used for calibration of look-up tables in engine control unit with developed criteria and tip-in rating functions. For this purpose, elastic driveline model is developed, and anti-jerk model is integrated to the model in MATLAB/Simulink modelling environment. Subsequently, model parameter tuning is performed, test maneuvers are simulated, and simulation results are compared with actual vehicle tests results. This study has demonstrated that the vehicle model is useful in determining initial values of the look-up tables in ECU software, but evaluation of the simulation results indicated that an advanced driveline and more importantly a detailed engine model are necessary to better represent the physical vehicle and to match vehicle test results. Therefore, model study gives approximate results and can be used; however, fine tuning in test vehicle is still required for optimum performance.

Potential future work may include multivariable optimization algorithms to be applied to engine control unit, and method performances may be analyzed and compared.

Optionally, driver characterization can also be studied to present the effectiveness of the algorithm. Since each driver has unique driving skills and usage profile of the vehicle, and criteria weights can be selected based on driving profile or drive modes, and maps could be updated to satisfy driver expectations.

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BIOGRAPHY

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PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

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<https://doi.org/10.17341/gazimmfd.1226530>



APPENDICES

APPENDIX-A: Terms

Backlash – The clearance between mechanical components in the driveline.

Lash – A shortened name for backlash. Frequently used interchangeably with the “Backlash”.

Surge – High frequency (> 15 Hz) driveline disturbance caused by the energy transfer during collision of backlash elements.

Clunk – Audible sounds that are the result of backlash crossing.

Jerk – Derivative of acceleration

Shuffle – First order driveline oscillation