UNIVERSITY OF GOTHENBURG

Evaluation of Model-Based Testing for Embedded Systems based on the Example of the Safety-Critical Vehicle Functions

Master of Science Thesis in the Software Engineering and Management

SHASHA LIU

University of Gothenburg
Chalmers University of Technology
Department of Computer Science and Engineering
Göteborg, Sweden, October 2012

Evaluation of Model-Based Testing (MBT) for Embedded Systems based on the Example of the Safety-Critical Vehicle Functions

SHASHA LIU

Supervisor: CHRISTIAN BERGER
Examiner: MIROSLAW STARON

University of Gothenburg
Chalmers University of Technology
Department of Computer Science and Engineering
SE-412 96 Göteborg
Sweden
Telephone + 46 (0)31-772 1000

[Cover:
Embedded systems in vehicle
Provided by Inxee Technologies Company]

Department of Computer Science and Engineering
Göteborg, Sweden October 2012

Acknowledgements

There are many people I would like to thank for helping me during my thesis work.

First, I would like to express my deepest appreciation to all of my teachers. Especial for my supervisor Assistant Professor Dr. Christian Berger, for his excellent guidance, approachable understanding and pertinent advices he has provided over the entire thesis work. Thanks for my examiner Associate Professor Dr. Miroslow Staron's useful feedback. I would also like to show my gratitude to my programme coordinator Assistant Professor Dr. Agneta Nilsson, for her guidance of thesis work process. I wish to thank Mr Joakim Jahlmar, for his writing language support.

Second, I would like to give a special thanks to Inxee Technologies Company, for their support to provide an image that used in my thesis cover.

Finally, I want to show my heartiest gratitude to my friends and families for their love and support. They are always there when I needed them.

Abstract

Along with the announcement of vehicle safety standards, e.g. ISO 26262, ESP and AUTOSAR, embedded systems are used widely to realize the safety function in the automotive domain. Due to the increased number of sensors involved in the system, one important problem to be solved is to obtain enough appropriate test cases to ensure that the implemented system functions are satisfying the software requirements specification.

This thesis describes the systematic literature review performed on Model-Based Testing (MBT) approaches that are available in the automotive domain, mainly focusing on finding the MBT approaches that create models directly from software requirements specification. Furthermore, by applying selected MBT approaches in two conducted running examples of safety-critical functions in the automotive domain, the study shows the advantages and disadvantages of using such approaches. The first running example is the Seat-Belt Reminder System (SBRS) that represents discrete signal processing embedded systems, and the second one is a type of continuous signal processing embedded system called Collision Detection System (CDS).

Table of Contents

List of Figures and Tables

1. Introduction & Motivation

Embedded software systems are used widely nowadays to realize comfort and safety functions in vehicles, planes, and trains domain. Along with the increased number of sensors involved in the systems, the development is getting increasingly complex. Hence, in order to ensure a reliable and safe operation, a thorough test is required for validating the expected behavior by the implementation. Furthermore, the important prerequisite of a thorough test depends on the relevant test cases [GG93]. It has been claimed that more than 50% cost for embedded systems development are caused by testing and error correction in the late development stage, and arguable selection of test cases is one of the main reasons [PFH+06]. Therefore, a test engineer is faced with the question of how to find enough appropriate test cases to ensure an effective and efficient thorough testing. As a common and popular solution, Model-Based Testing (MBT) plays an important role in testing automotive embedded systems [CHG12].

In this thesis, the model describes the formal representation of valid and allowed input stimuli sequences combined with expected output values, which can be used to derive test cases. Model-based Testing is an approach to design possible test cases in a platform-independent manner from which platform-specific test cases are derived automatically [UL06]. It is used as a cost-effective approach for embedded systems, especially for the systems in the automotive area. Model Based Testing can detect system under test fault in the very early stage. It also provides requirements traceability [NE08]. In model-based testing, the expected behavior is created as model from the System Under Test (SUT), and the test cases are derived automatically from the model.

The purpose of this study is using a Systematic Literature Review (SLR) to find recent available MBT approaches which are used for validating embedded systems in the automotive domain and to evaluate those approaches with two running examples. The outcome of research is to provide a suggestion for test professionals to choose the proper MBT approaches by considering merit and demerit for generating enough appropriate test cases. This study mainly focuses on the MBT approaches that create models manually directly based on two example specifications to derive test cases, see figure 1.

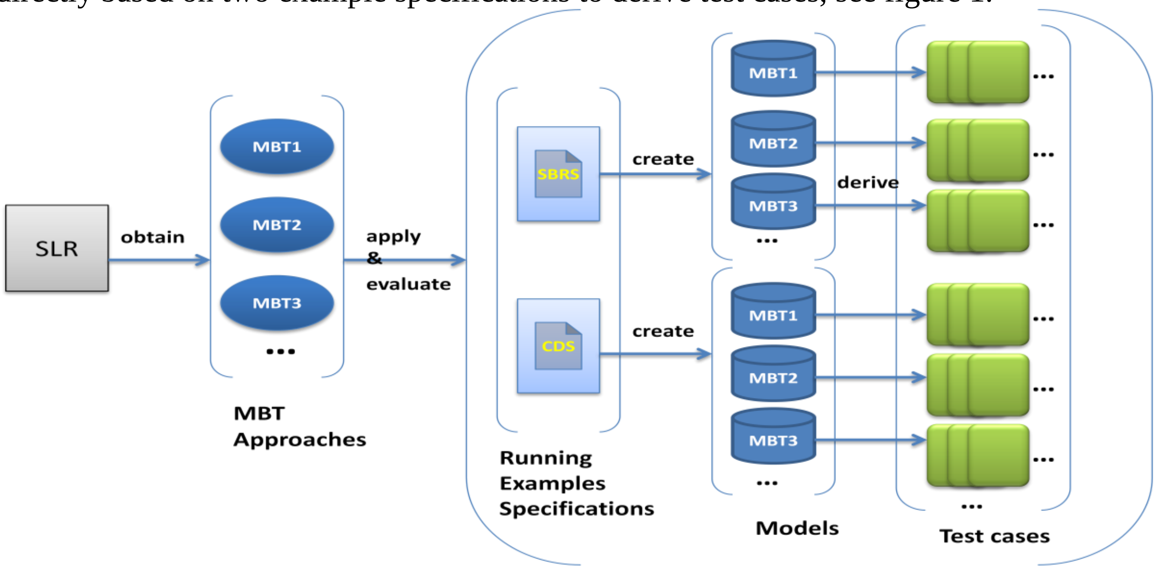


Figure 1 Thesis Scope Overview

The paper remainder is organized as follows. Section 2 presents the related work for systematic review on model-based testing. Section 3 describes the research method in detail. Section 4 provides the available MBT approaches information. After that, two running examples are demonstrated in section 5. Section 6 provides the results after evaluating the MBT approaches with running examples. Finally, the conclusion and outlook is shown in section 7.

2. Related Work

Since the 1990s, many model based testing methods has been presented [ZZZ+10], which attracts some researchers to do study on it.

A survey on modeling language shows that behavioral model can be taken from many forms, like diagrams, grammars, tables and control flow graphs etc. Those models have two main functions; one is used to describe the set of stimuli applied to the SUT, the other one is to describe the possible responding system responses to those stimuli. That study provides some guidelines to help in the decision between different types of testing modeling language [HKO06].

Dias-Neto et al. did a systematic review on model-based testing approaches that were published between 1990 and 2006. This research shows that 66% MBT approaches are applied for system testing and they are suitable to support structural testing from software requirements. The investigation indicates that 60% models are derived from software requirements. 23.2% models are described using UML diagrams. UML statechart, class and sequence diagrams are most often used in particular, and 76.7% models are described using non-UML notations that include finite state machine and Z Specification [DSV+07].

A systematic review [DT08] provides supporting the MBT approaches selection for software projects. That study proposed an infrastructure with some activities to provide criteria for choosing MBT approaches. Those activities are software projects characterization, adequacy level and indicators for the selection of MBT approaches, MBT approaches combination charts, and MBT approaches measurement and evaluation.

This study mainly focuses on reviewing the MBT approaches that used for embedded systems, especially in the automotive domain, from 2007 until 2012.

3. Research Methodology

This section illustrates the research goal and the research questions of this study. In this thesis, systematic literature review and case study were used to address the research questions, which help to achieve the research goal.

3.1 Research Goal

This study intends to achieve the following goals:

- Find recent available MBT approaches for validating embedded systems.
- Identify the MBT approaches for validating embedded systems in the automotive domain.
- Evaluate the identified MBT approaches by applying such approaches with two automotive safety functions systems examples.
- Summarize the advantage and disadvantage of applied MBT approaches.

3.2 Research Questions

In order to achieve the goal (see 3.1), the following research questions are listed:

- Which MBT approaches are available?
- Which MBT are applicable for embedded systems?
- What are their particular strength and weaknesses?

3.3 Systematic Literature Review

Systematic Literature Review (SLR) is a method used to identify, evaluate and interpret all available publications relevant to a particular research topic [SSM07]. In this study, a SLR was conducted to identify all available Model-Based Testing (MBT) approaches to validate automotive embedded systems, and to evaluate each selected MBT approach and after that, to interpret the research results.

This study followed an applied search strategy that includes five parts. The first part illustrates the search queries, after that the search resources are listed, and the third part shows how the search queries are applied with search resources, and the fourth section demonstrates the selection process. Finally, the last part provides the results.

3.3.1 Search Strategy

This strategy is used to guide the search for the study. It contains search queries and search resources.

3.3.1.1 Search Queries

The search queries have been produced by breaking down the research questions and topic according to the population and intervention criteria where population means the application area, intervention is the software methodology used to address a specific problem [SSM07]. In this study, the keywords for searching are listed as follows:

- Population: embedded systems , automotive embedded systems, active safety systems and safety critical systems
- Intervention: model based testing approaches

Each search term contains two phases by constructing Boolean ‘AND’, hence, five search queries are conducted as follows:

1) "model based testing" AND approaches
2) "model based testing" AND "embedded systems"
3) "model based testing" AND "automotive embedded systems"
4) "model based testing" AND "active safety systems"
5) "model based testing" AND "safety critical systems"

3.3.1.2 Search Resources

This study has used eight digital libraries that are related to software engineering [Tur10] by applying the defined search queries. The digital libraries are listed below:

1) ACM
2) IEEE Xplore
3) SpringerLink
4) ScienceDirect
5) Citeseer
6) Google Scholar
7) Web of science
8) SCOPUS

3.3.2 Search Criteria

The exclusive criteria are used to exclude the results that unrelated to the study, whereas inclusive criteria are used to include the relevant results.

3.3.2.1 Exclusive Criteria

- Repeated articles in different libraries
- Duplicated topic from the same author
- Not describe the mode based testing itself
- Not related to testing for automotive related systems, e.g. GUI testing, web testing, medical systems, printer and calculator
- Repeated in different search queries results
- Model derived from source code

3.3.2.2 Inclusive Criteria

- Covered systems are related to automotive embedded systems, track-bounded embedded systems and flight related systems
- Model derived from requirement specification

3.3.3 Search and Selection Process

In order to obtain the most relevant articles with the research goal (see 3.1) from tens of thousands of results, the entire process followed four steps. First, search queries were applied into digital library by combining two search factors i.e. published between 2007 and 2012 and each string in the paper’s abstract completely, to obtain the initial search results. Second, apply the exclusive criteria to exclude the unrelated results and inclusive criteria to include the related results. Third, extract data from selected final search results. Finally, classify the papers into classes based on different extracted approaches. The entire procedure is shown in figure 2.

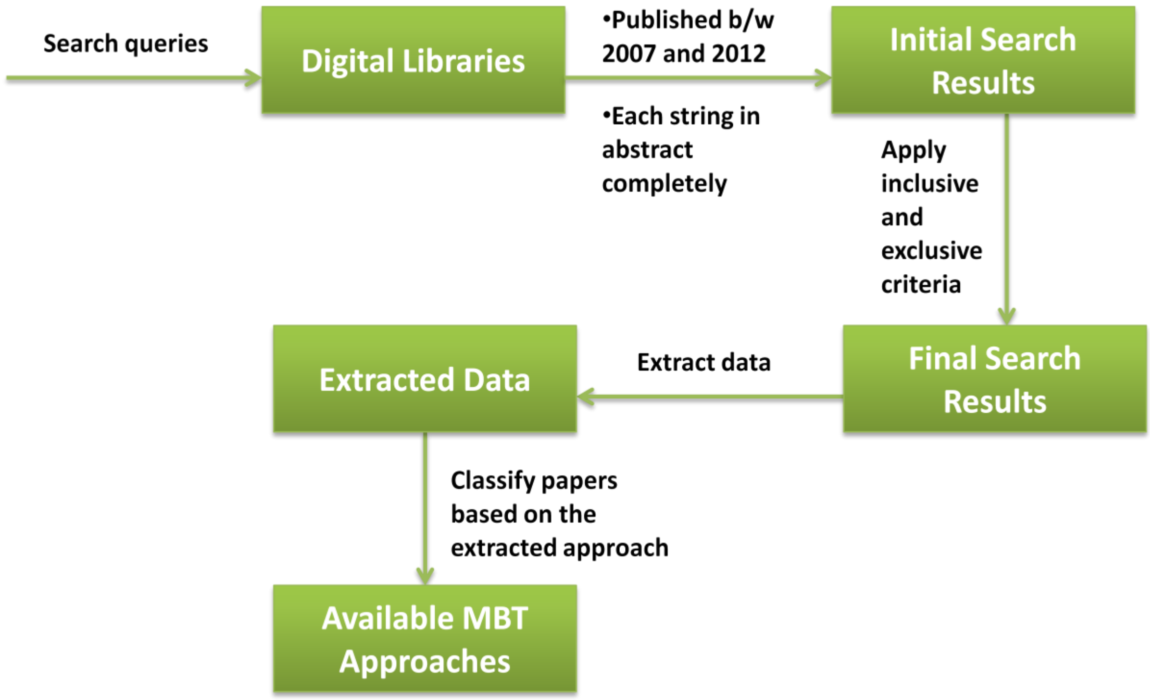


Figure 2 Search and Selection Process

3.3.4 Search Results

902 papers were obtained in total after the first round search by applying the search queries. Table 1 shows that the number of model based testing publications has been increasing in the past five years. Among this, 569 out of 902 (63%) papers were published between 2009 and 2011. 85% publications were found from ACM, IEEE Xplore, Web of Science and SCOPUS digital libraries. Figure 3 demonstrates that there is a dramatic increasing trend for publications on search query '"model-based testing" AND "embedded systems" ' in 2010 and 2011 years.

Source	2007	2008	2009	2010	2011	2012	No. of papers
ACM	20	28	39	47	51	20	**205**
IEEE Xplore	10	17	21	30	36	14	**128**
SpringerLink	7	7	11	13	14	8	**60**
ScienceDirect	6	1	3	6	0	6	**22**
Citeseer	4	2	1	3	0	0	**10**
Google Scholar	4	7	7	3	12	6	**39**
Web of science	26	26	52	18	21	8	**151**
SCOPUS	34	41	51	66	64	31	**287**
Total	**111**	**129**	**185**	**186**	**198**	**93**	***902***

Table 1 Initial Search Results

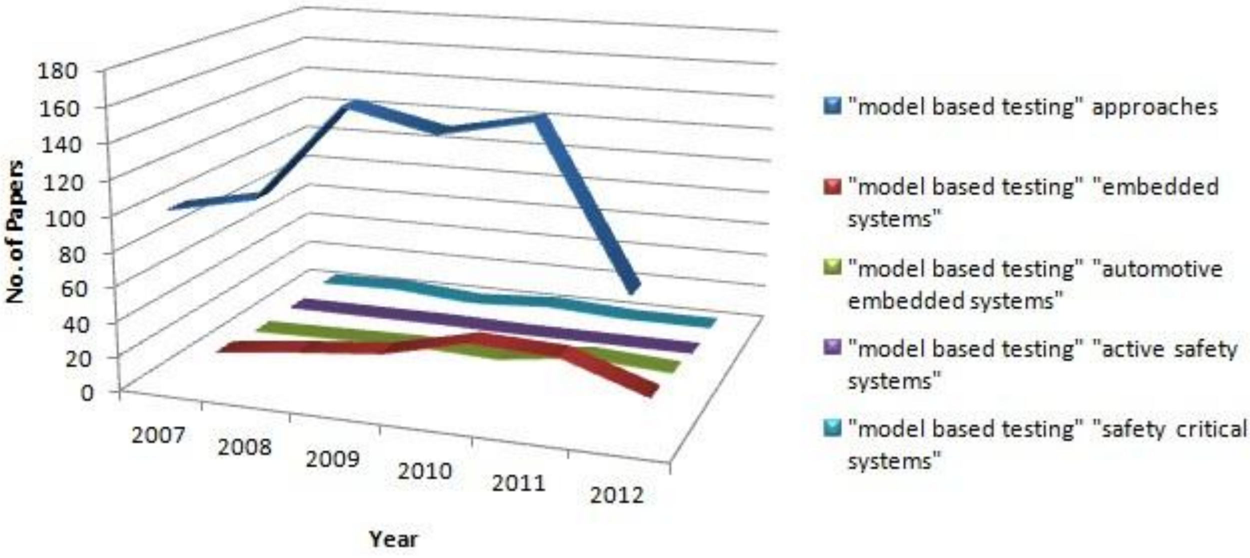


Figure 3 Different Search Queries Results in Different Year

3.3.5 Data Extraction Strategy

This section provides the data extraction strategy in detail. It contains two sub sections. The first part demonstrates the data that extracted from each selected paper according to 8 criteria. Available Model-Based Testing (MBT) approaches extracted from the first sub section (3.3.5.1) is illustrated in the second part (3.3.5.2).

3.3.5.1 Extracted Data

After applying with exclusive and inclusive criteria (see 3.3.2), 27 selected papers have been analyzed. The data has been extracted from each selected paper by using 8 criteria. The reference column indicates the citation of each paper. The detailed information is illustrated in table 2. Due to the space limitation, table 2 has been divided into two sub-tables.

1) *Author/Year*
2) *Testing level* : The technique applicable testing level.
3) *Applicable Domain* : The domain applied for the approaches.
4) *Approaches/Techniques* : The approaches have been used.
5) *Behavior Model* : The behavior model used for the approaches.
6) *Tool Support* : The supported tool mentioned for the approaches.
7) *Case Study/Example* : Case study or examples provided in the paper.
8) *Model Origin*: It shows the original source of model that described in the paper, from source code or from requirement specification.

Table 2 Extracted Data of Selected Papers

Reference	Author/Year	Testing Level	Applicable Domain	Approaches/ Techniques	Behavior Models	Tool Support	Case Study/ Example	Model Origin
[PVA+12]	Pontes et al., 2012	Integration Testing	Space Embedded Software	Conformance and Fault Injection(CoFI)	Finite State Machine (FSM)	Yes(Condata)	On-board Data Handling Satellite Software	Req
[LPG11]	Lasalle et al., 2011	Not Defined (ND)	Automotive Mechatronic Systems	End to End Test MBT Framework	UML &OCL	Yes(Test Designer™)	Vehicle Front Axle Unit	Req
[CSV10]	Cristia et al., 2010	Unit ,System , Acceptance Testing	Embedded Systems	Statechart based testing & Z based testing	Statecharts Model , FSM, Z-bases Testing Tree	Yes	Software Embedded into the Payload Data Handling Computer	Req
[LG10]	Lochau et al., 2010	Integration Testing	Embedded Control Systems	Statechart-like Formalisms	Stateflow Automata	Yes(Matlab/ Simulink)	Car Door Controlling System	Req
[ABJ+10]	Aichernig et al., 2010	ND	Hybrid Systems	Abstraction	Qualitative Action Systems	Yes	Two –tank System	Req
[BHK09]	Belli et al., 2009	System Testing	Automotive Electronic Control Units	Event Sequence Graph(ESG)	ESG Graphs, Classification Tree	Yes(CANoe)	Adaptive Cruise Control Unit	Req
[TBL+09]	Tamisier et al., 2009	ND	Embedded Systems	Test Bench Scripting Language(TBSL)	UML/XML	ND	3D Time-Of-Flight Optical Sensor	Code
[Zan08]	Zander-Nowicka, J., 2008	Component-in-the loop and Integration Tests	Automotive Real-time Embedded Systems	Model-in-the-Loop for Embedded System Test(MiLEST)	In Geneal	Yes(Matlab Simulink/ Stateflow)	Speed controller, Adaptive Cruise Control	Req
[NE08]	Nakao et al., 2008	System Testing	Embedded systems with safety critical functions	Sequence-Based Specification(SBS)	SBS Model	ND	Car Door Control Unit	Req
[BS12]	Berger et al., 2012	ND	ND	SBS	SBS Model	ND	Auxiliary Heating System	Req
[CP07]	Carter et al., 2007	ND	Embedded Control Systems	SBS	SBS Model	Yes(Simulink)	Automotive Power Window	Req
[LBL+11]	Lasalle et al., 2011	ND	Embedded Systems	SysML4MBT Notation	SysML4MBT model	Yes	Car lighting system	Req
[KHE11]	Kloos et al., 2011	ND	Safety Critical Embedded Systems	Fault Tree Analyses (FTA)	Fault Tree & a Behavior Model	Yes	Automation Modular Production System	Req

Reference	Author/Year	Testing Level	Applicable Domain	Approaches/ Techniques	Behavior Models	Tool Support	Case Study/ Example	Model Origin
[LPW11]	Iyenghar et al., 2011	ND	Resource Constrained Real Time Embedded systems	UML and UTP (UML Testing Profile)	UML	Yes	Spark Extinguishing System	Req
[JB11]	Junior et al., 2011	ND	Embedded Critical Systems	W-method & Wp-method & G-method	Finite State Machine	Yes	ND	Req
[SHJ11]	Schlick et al., 2011	ND	Embedded Systems	Combine Fault and Model Based Testing	UML State Machine	Yes	Car Alarm System	Req
[DL11]	Davies et al., 2011	ND	Flight Critical Software Systems	Formal Methods and Statistical Tools	Simulation model	Yes	Air Transportation System	ND
[WAE+11]	Wu-Hen-Chang et al., 2011	ND	ND	Testing and Test Control Notation 3 (TTCN-3)	Finite Machine Model	Yes	Alternative Bit Protocol	Req
[MWF+11]	Mitsching et al., 2011	ND	Real Time Embedded Systems ,Safety Critical Systems	Timed testing views	Timed automata/views	Yes (UPPAAl)	Traffic Light System	Req
[LWW10]	Lindlar et al., 2010	System testing	Continuous Control Systems	Evolutionary Testing & Time Partition Testing(EvoTPT)	Finite State Model	Yes (Matlab/ Simulink)	Automotive Cruise Control system	Code
[MTL10]	Malik et al., 2010	ND	Complex Systems	Integrate UML, UML-B (and Qtronic Test Generator Tool	UML/ UML-B Models	Yes (Conformiq Qtronic Generator Tool)	Mobile Switching Server	Req
[FGM+10]	Ferrari et al., 2010	ND	Railway Signaling Systems	Simulink/Stateflow	Simulink/ stateflow	Yes	Train Protection System	Code
[YXD09]	Yu et al., 2010	ND	Safety Critical Systems	ND	Markov Chain, FSM	Yes	Train Control System	Req
[ZZZ+10]	Zhao et al., 2010	System Testing	Safety Critical Systems	Coloured Petri Net (CPN)	CPN model	Yes(CPN tool)	European Train Control System Level 2 (ETCS-2)	Req
[CAO+08]	Cartaxo et al., 2008	ND	Embedded Systems	ND	Sequence Diagram	Yes(LTS-BT-se)	Self-defined Scenario	Req
[Pel08]	Peleska, 2008	ND	Safety Critical Systems	Integrate Abstract Interpretation,	Intermediate Model	Yes	C Functions and C++ methods	Code
[KH07]	Kollmann et al., 2007	ND	Safety Critical Systems	Multi-object Checking	Sequence Diagram	Yes	Railway Interlocking	Req

3.3.5.2 Extracted Available MBT Approaches

This study focuses on the approaches that create model from software requirements specification only according to the thesis scope (see figure 1), hence, the papers that describe creating models from source code were excluded. Ten different approaches were obtained from table 2 in total. The detailed information is shown in table 3.

Approach/ Technique	Amount of Papers	Paper References
Sequence Based Specification	3	[NE08],[BS12],[CP07]
Event Sequence Graph	1	[BHK09]
Classification Tree	1	[BHK09]
Conformance and Fault Injection (CoFI)	1	[PVA+12]
Unifies Modeling Language(UML)	6	[LPG11],[LPW11],[SHJ11],[MTL10], [CAO+08],[KH07]
Stateflow Automata	1	[LG10]
Fault Tree Analysis	1	[KHE11]
Makov Chain	1	[YXD09]
Coloured Petri Net	1	[ZZZ+10]
Finite State Machine	3	[CSV10],[PVA+12],[WAE+11]

Table 3 Available MBT Approaches

Figure 4 below demonstrates the usage status of MBT approaches used for embedded systems in the past 5 years, i.e. from 2007 until 2012.

- Compared to the survey [DSV+07] from 1999 to 2006, there are many new MBT approaches conducted from 2007 to 2012, but UML and finite state machine are still most often used.
- 2010 and 2011 are the most active years, the reasons might be the following:
    a. IS0 26262 standard “Road vehicle – Functional safety” was published in 2011. It is mandatory during the development of safety functional requirements [ISO12].
    b. Increase of active safety systems in vehicles
        - From 1 Nov 2011, ESP (Electronic Stability Programme) must be equipped to all new car and light commercial vehicle models mandatorily. As the news point out “ESP equipped with all new vehicle models as standard paves the way for increased use of driver assistance systems and sensors that monitor vehicle surrounding” [Rob11].
        - Model-Based Testing is more suitable for validating safety function of braking guards.
    c. Trend of increased usage of modeling techniques [ZZZ+10].
    d. AUTOSAR (AUTomotive Open System ARchitecture) is open and standardized automotive software architecture [AUT12a]. It paves the way for innovative automotive electronic systems that further improve safety [AUT12b].

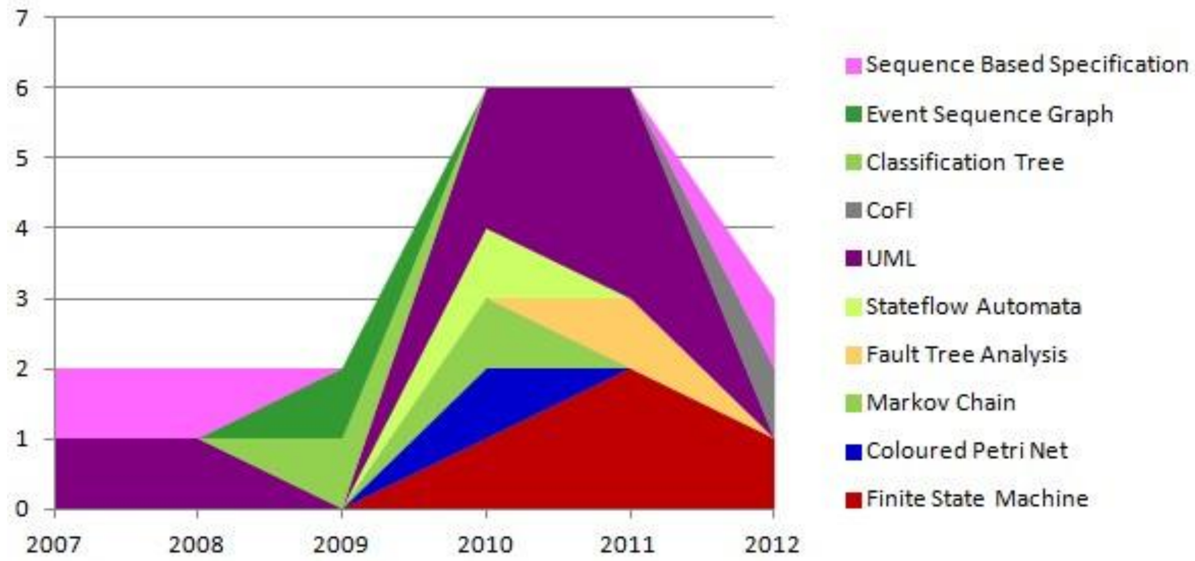


Figure 4 Available MBT Approaches Trend

3.4 Case Study

The case study was used to validate the MBT approaches that obtained from the systematic literature review, with two simplified systems specifications. One represents discrete signal processing embedded system that provides discrete input stimuli, the other one is type of continuous signal processing embedded system that produces continuous input stimuli. By following the procedures of the methodology that described in the paper, the MBT approaches were applied with two running examples. The detailed information is shown in section 5.

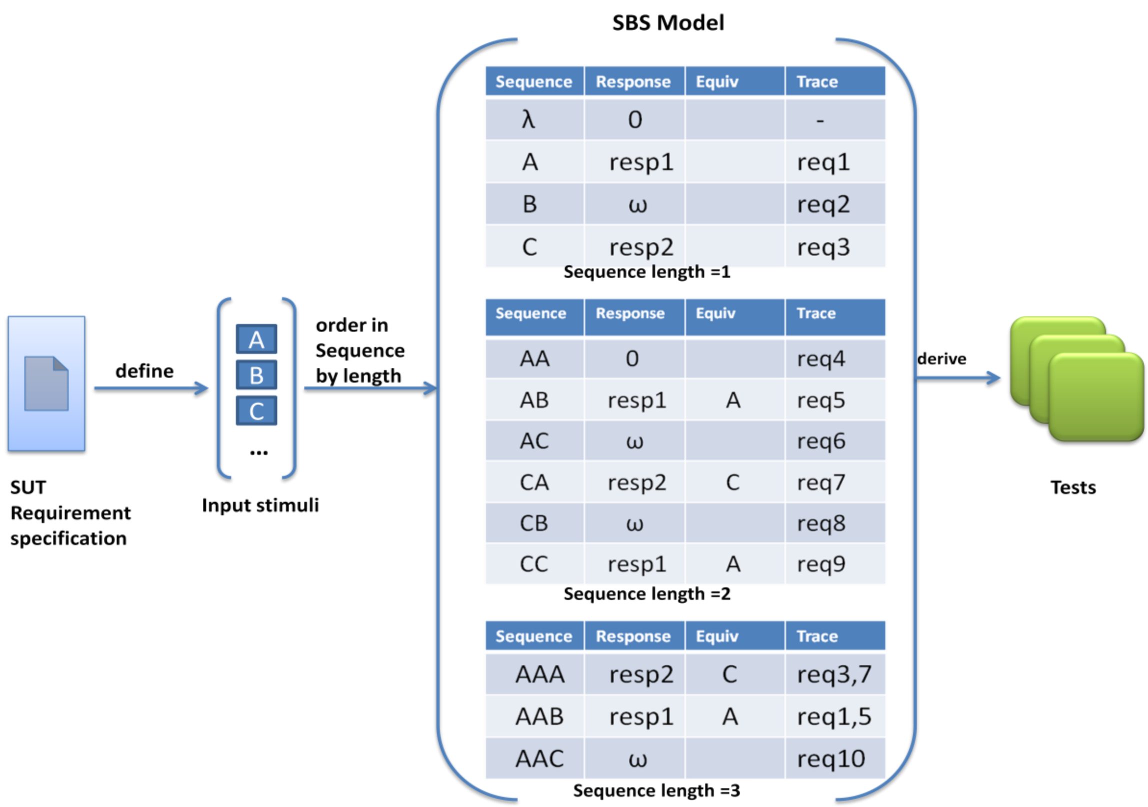
4. Available Model-Based Testing Techniques

This section provides the brief description of Model-Based Testing (MBT) approaches that extracted from section 3.3.5.2. For easy understanding, each approach is described with the corresponding diagram.

4.1 Sequence Based Specification (SBS)

Sequence Based Specification (SBS) is a systematic approach used to ensure the completeness and correctness of the specified requirements in the very early stage of development. This method treats the system as a black-box by only considering the inputs and outputs rather than knowing the internal structure of the system [BS12, BR10].

Figure 5 is used to demonstrate how SBS approach works. First define the input stimuli from the system requirements specification and then organize the stimuli sequences in order by length. Each sequence is given a required response that specified in the requirement specification. Sign λ means empty input, ω represents response for the illegal input stimuli sequences and 0 represents response for the input stimuli that don't produce any external observable behavior. If a further stimuli sequence, e.g. AB, leaves the system in the same condition with the responses of a previously sequence, e.g. A, then sequence AB is equivalent to A. As shown in figure 5, A is stated in Equiv column of sequence AB. The corresponding requirement for each sequence and its response is noted in Trace column. The input stimuli sequences that are legal or don't equivalent to any previous sequence are extended by each stimulus. The input stimuli sequences that are illegal or has equivalent relation to another input stimuli are not extended. The model steps stop when there is no more stimuli sequences can be extended [BR10]. In figure 5, the model process stops at sequence length 3, because there is no sequence stimuli can be extended.



Sequence	Response	Equiv	Trace
λ	0		-
A	resp1		req1
B	ω		req2
C	resp2		req3

Sequence	Response	Equiv	Trace
AA	0		req4
AB	resp1	A	req5
AC	ω		req6
CA	resp2	C	req7
CB	ω		req8
CC	resp1	A	req9

Sequence	Response	Equiv	Trace
AAA	resp2	C	req3,7
AAB	resp1	A	req1,5
AAC	ω		req10

Figure 5 Sequence Based Specification Approach Overview

4.2 Event Sequence Graph (ESG)

Event Sequence Graph (ESG) is a technique used to model the interactive systems behavior by using a collection of event sequence graphs. This approach uses a finite set of ESGs to model the desirable behavior of SUT, and then invert each ESG to represent the undesirable behavior algorithmically. Finally, the ESGs and their inventions, called CESG, are used for generating test cases [BNB+05], see figure 6.

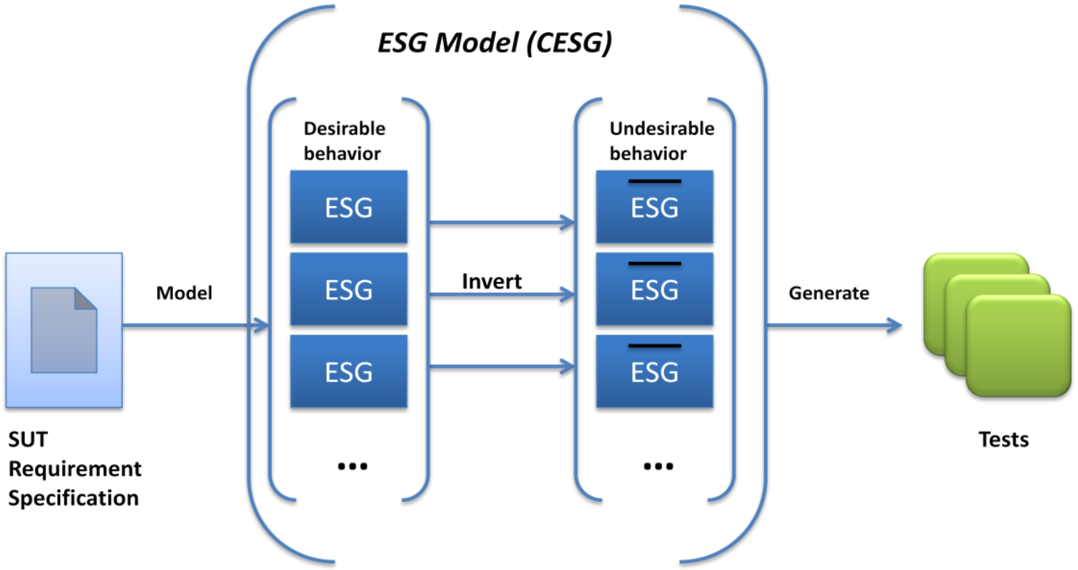


Figure 6 Event Sequence Graph Approach Overview

An event sequence graph is a directed graph that contains a set of events and their relations, where the events can be divided into two sub-categories: input stimuli and system response. And the incoming arrow with no source and outgoing arrow without target are considered as entry and exit node respectively [BNB+05]. Figure 7 (a) shows the ESG diagram with three events and their interactions. Event A, B and C are connected by arrows, an arrow from A to C means that event C can follow event A. Figure 7 (b) demonstrates the inversion of ESG (figure 7(a)). The Complete Event Sequence Graph (CESG) is made of ESG and its inversion, see figure 7 (c).

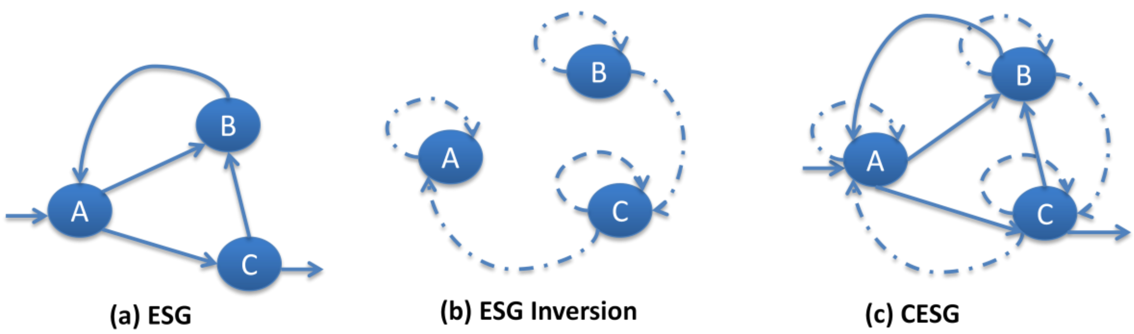


Figure 7 ESG Diagrams

ESG approach includes some terminologies [BNB+05] that needed to be known before using. In order to be easily understandable, the following terms will be explained with the help of figure 7 (c).

- Event Pair (EP) : each edge of the ESG, e.g. AB, CB.
- Event Sequence (ES) : the sequence of n number of consecutive edges of ESG.
- Complete Event Sequence (CES): the ES starts at the entry of the ESG and ends at the exit. The set of CESs specify the system functions, which can be treated as test cases. E.g.AC.
- Faulty Event Pair (FEP): Event pair of ESG inversion's edges, e.g. AA, BC.
- Faulty Event Sequence (FES): the sequence of n number of consecutive edges of FESG.
- Faulty Complete Event Sequence (FCES): is conducted by set of FEPs, each FEP starts at entry node can be treated as FCES. Furthermore, the FEP doesn't start at entry node can be extended as FCES by the EP that starts at entry node and its last symbol is the first symbol the FEP. E.g. FEP: BC can be extended as FCES by adding AB, and then ABC is FCES.

In ESG approaches, CES based test cases are proposed to succeed the test whereas FCES based test cases are supposed to fail the test [BNB+05].

ESG approach uses exception handler to execute defense actions for responding the undesirable input event sequences. The system will be brought by appropriate defense action from current state to less risky state when the threats detected. Defense actions are enforced sequences of events, which specified based on the defense matrix. The set of exception handlers and defense matrix are specialized by domain expert according to the risk of the given unexpected behavior. The states risky level is conducted by using risk ordering relation. The risk ordering relation defines the comparison of states' risky level [BNB+05].

4.3 Classification Tree

Classification tree method comes from partition testing, which is used to support the test cases determination in a systematic way [GG93]. According to figure 8, classification tree partitions the input domain of SUT into different classifications according to different aspects, and each classification is continued to be divided until cannot be divided further. All the impartible classes are combined as a table, called combination table, which used to form test cases. The test cases are obtained by selecting combination of different classes [BHK09]. The choosing of combination of classes decides the test cases number. The minimum number requires each class to be used at least once, and the maximum number requires each logical compatible combination of classes as a test case. As a rule of thumb, the minimum should always be satisfied [GG93].

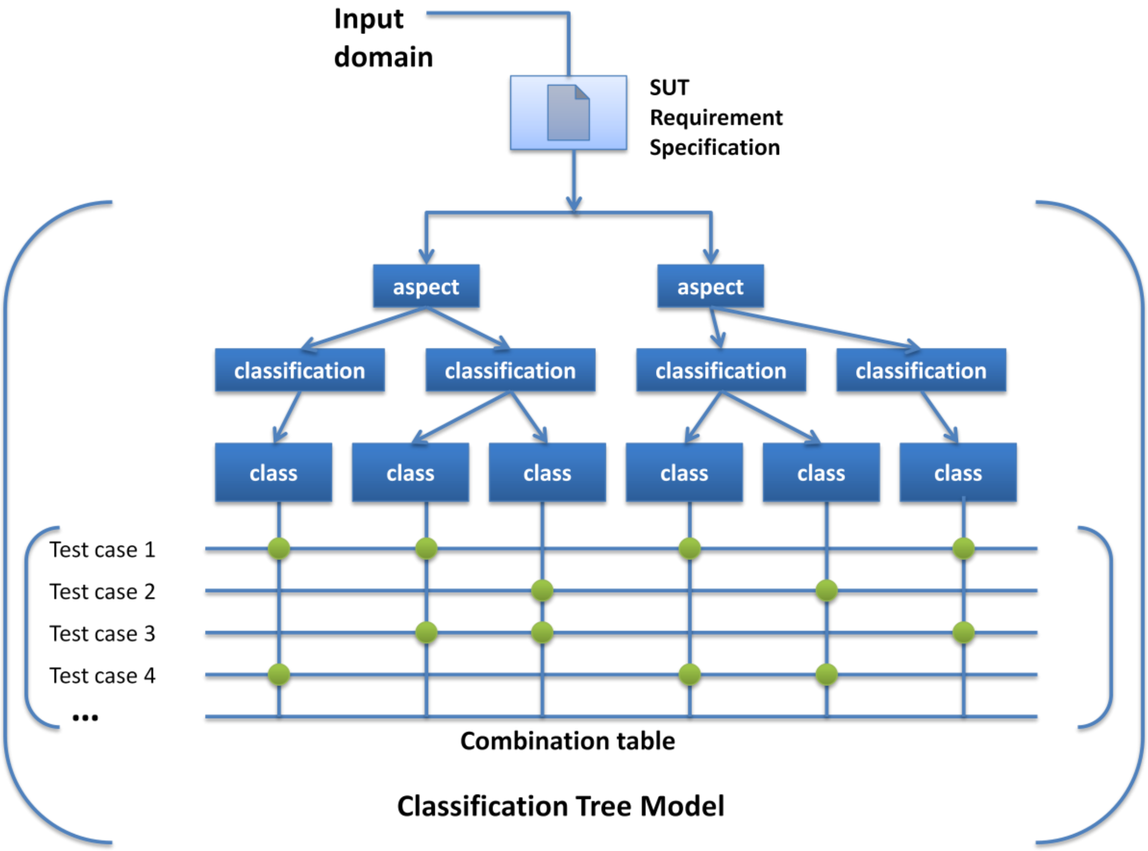


Figure 8 Classification Tree Approach Overview

4.4 Conformance and Fault Injection (CoFI)

Conformance and Fault Injection (CoFI) is a systematic way of model-based testing approach used to create test cases for critical software [AMV+06]. It has been applied to space embedded systems traditionally. According to figure 9, there are 3 steps to follow the CoFI method. First of all, identify all the services of System Under Test (SUT) specification. Secondly, create a set of Finite State Machine Models (FSMs) for each service. Each finite state model should represent system services and behavior types under four different input classes. These four different input classes are: normal, specified exceptions, inopportune inputs and invalid inputs caused by hardware faults. Finally, derive test cases from the created models by applying switch cover algorithm that all the reachable paths from the initial state of the model are covered [PVA+12].

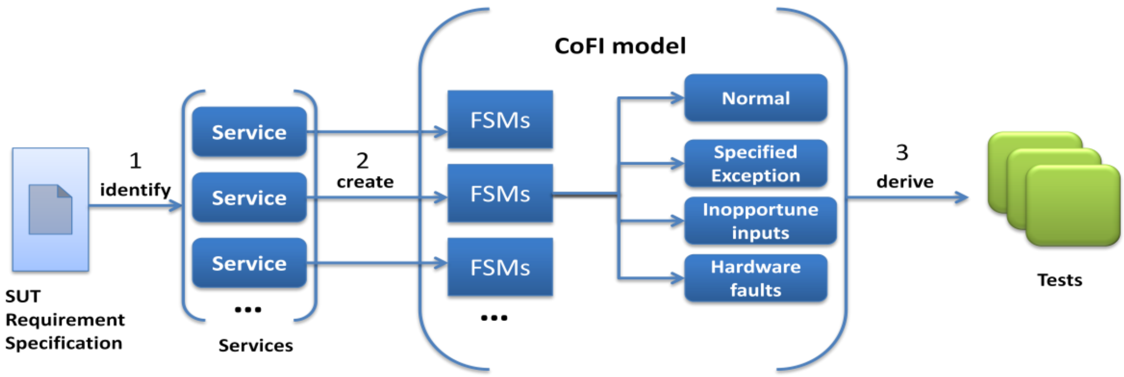


Figure 9 CoFI Approach Overview

4.5 UML/OCL

This tooled approach is proposed to validate automotive mechatronic systems. This method takes UML (Unified Modeling Language) /OCL (Object Constraint Language) model that describe the stimuli of SUT environment as input [LPG11]. In this method (see figure 10), the UML model contains class diagram and object diagram. The class diagram is used to define the static view of environment, which contains entities, the relationships between entities and actions. The object diagram defines the initial value of the entities that represent the environment. OCL formula is used to annotate the class diagram operations, which formalizes the expected behavior [LPG11].

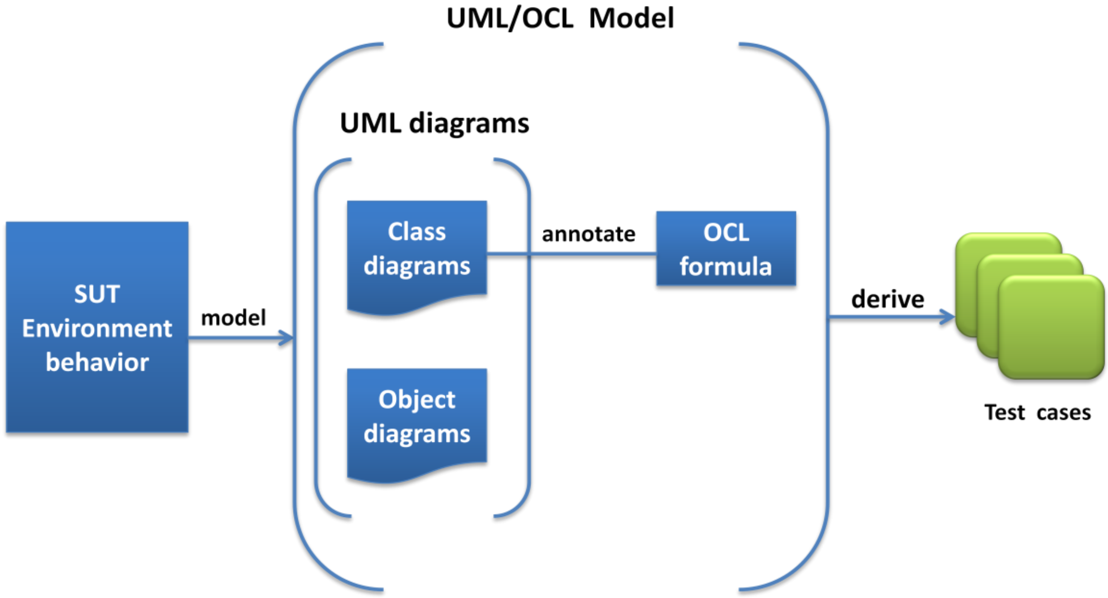


Figure 10 UML/OCL Approach Overview

4.6 Stateflow Automata

In order to overcome the unexpected safety problem occurred during feature interactions at the system integration level, a MBT method is described for efficiently generating test cases that particularly aim at feature interaction analysis [LG10]. According to figure 11 feature interactions of SUT specification are characterized in a formal way as a functional architecture model that contains set of three types of components. System components part includes input value read by the component, output value changed by the component and internal behavior that used to implement the components functionality. Sensor components contain only output value that used to deliver. Actuator components only have input values that will affect them. And then, the internal behavior of system components will be modeled by using stateflow automata technique. Stateflow Automata technique, as a part of Matlab/Simulink tool set, is a Statechart-like [LG10]. It contains two sub-states, basic states and composite states that include XOR states and AND states. XOR states are used to lead the hierarchical scopes of the states and the AND states are introducing the concurrent sub machines. Each sub state includes the source state, the destination state and their transition relation. From source state to destination state, ECA rules must be followed. E represents the events occur when system triggers the transition. C stands for conditions that needed to be satisfied when transition wants to fire. A represents the action that performed when the transition is taken. The test cases are generated from behavior model stateflow automata model with the help of Matlab/Simulink tool [LG10].

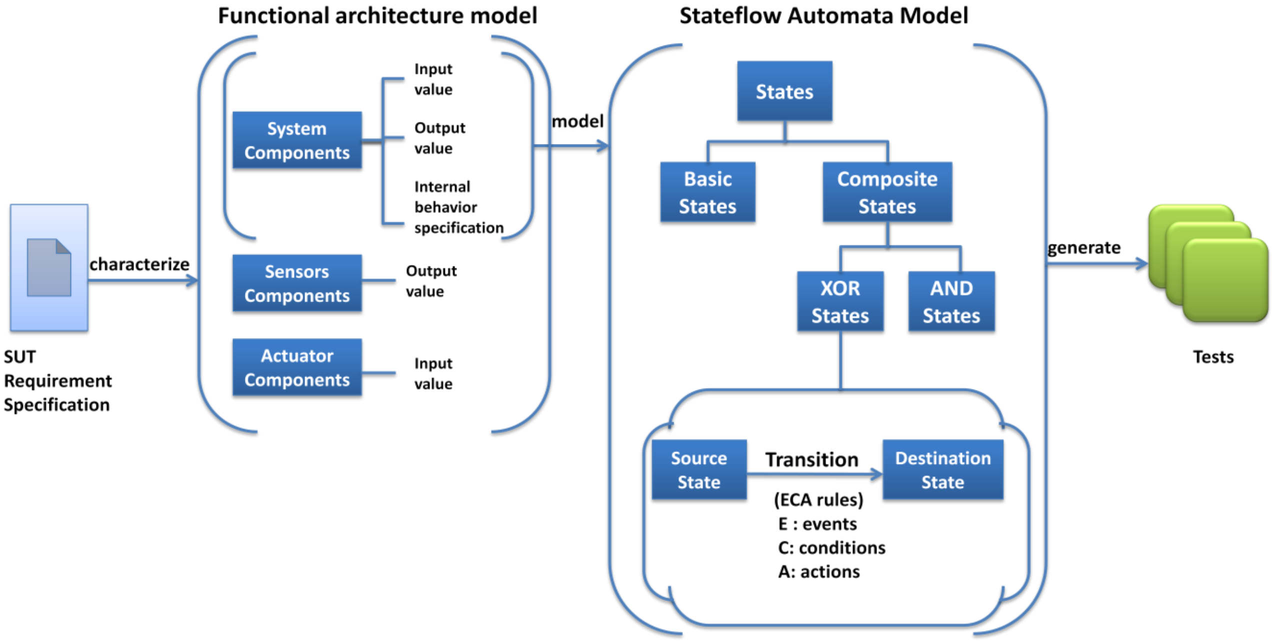


Figure 11 Stateflow Automata Approach Overview

4.7 Fault Tree Analyses (FTA)

FTA is a deductive top-down method that considers information derived from the safety analyses [KHE11]. According to figure 12, fault tree model contains a failure mode as top event. The failure mode contains a set of event set that used to describe the potential safety-critical situation and those situations must be handled by the system. Each event set includes a set of basic events, and these events can either cross the interface or occur inside the system. The basic events can be divided into four types: external, controllable, observable and internal. External events occur out of the system boundary and don't imply input stimuli and system responses. Controllable events correspond to the sequence of stimuli to the system. Observable events represent condition on the system response. Internal events describe the events that happen inside the system completely, which is the opposite of external events. In order to avoid extremely large fault tree, this method prioritize test scenarios based on their likelihood and impact. The higher critical one will be selected for testing. The test cases are derived from the combination of a behavior model (FSM) and fault tree model [KHE11]. The FSM modeling process please refers to section 4.10.

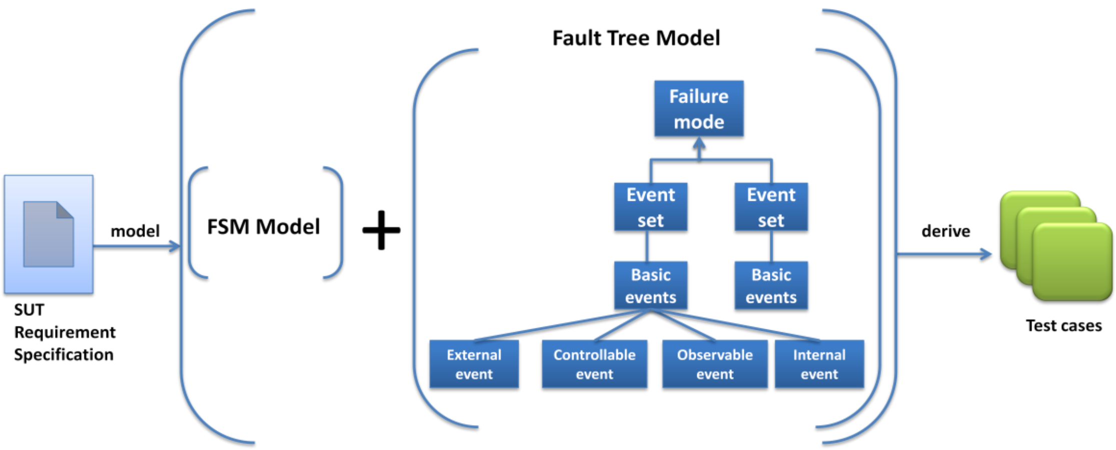


Figure 12 Fault Tree Approach Overview

4.8 Markov Chain

This Model-Based Testing (MBT) approach is proposed to test safety-critical software systems based on safety requirements [YXD09]. According to figure 13, the models are derived from the SUT requirements. The FSM model is derived from the system functional requirements and markov chain model is extracted from the system safety requirements. The detailed information of FSM modeling method, please refer to 4.10. In Markov Chain modeling method, the state space can be divided into three state subsets: Normal State Subset (NSS), Fail-Safe Subset (FSS) and Risky State Subset (RSS). NSS state subsets cover all the predefined safety control functions and all the controlled objects. FSS state subsets include all the definitely abnormal inputs and the caused failures results. RSS state subsets cover all the indefinitely abnormal inputs and the caused failures results. The FSS and RSS are from the field experts and practice [YXD09].

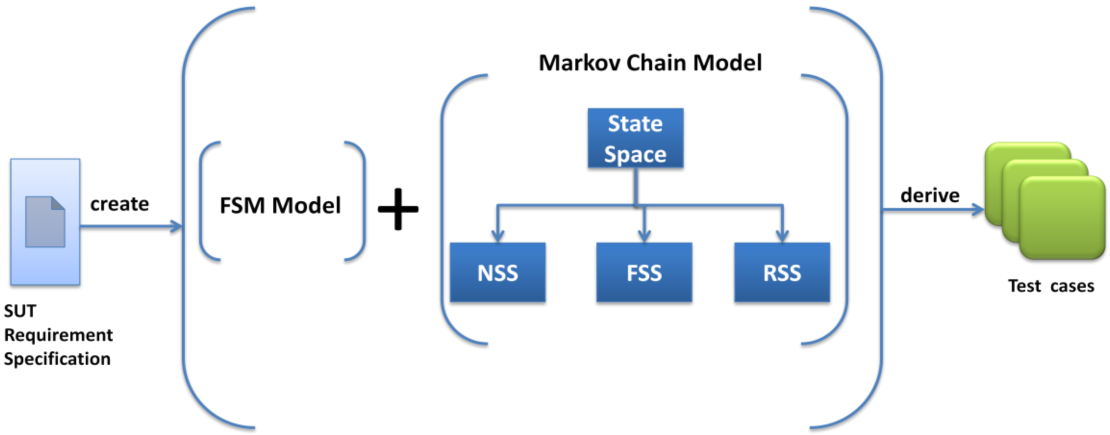


Figure 13 Markov Chain Approach Overview

4.9 Coloured Petri Net (CPN)

CPN is an extended Petri Nets which is a graphical and mathematical modeling method proposed by Kurt Jensen. It can be used to model systems with complex procedures for many systems, e.g. communication protocols, distribution systems and automated production [ZZZ+10].

In figure 14, the CPN model contains three main parts: input ports, conditions and output ports. Input ports include the finite set of input data, and output ports is made up of finite set of output data. The conditions have two sub parts: start condition and end condition. Start condition contains set of fusion places (GF_{SC}, IF_{SC} in figure 14) and set of internal input ports (IP). End condition contains set of fusion places (GF_{EC}, IF_{EC} in figure 14) and set of internal input ports (OP). The test cases can be derived from the CPN model by following two rules. The first one is GF_{SC} and GF_{EC}, IF_{SC} and IF_{EC} cannot be empty at the same time. The second one is that the situation $(GF_{SC} = GF_{EC}) \cup (IF_{SC} = IF_{EC})$ cannot exist in one test case [ZZZ+10].

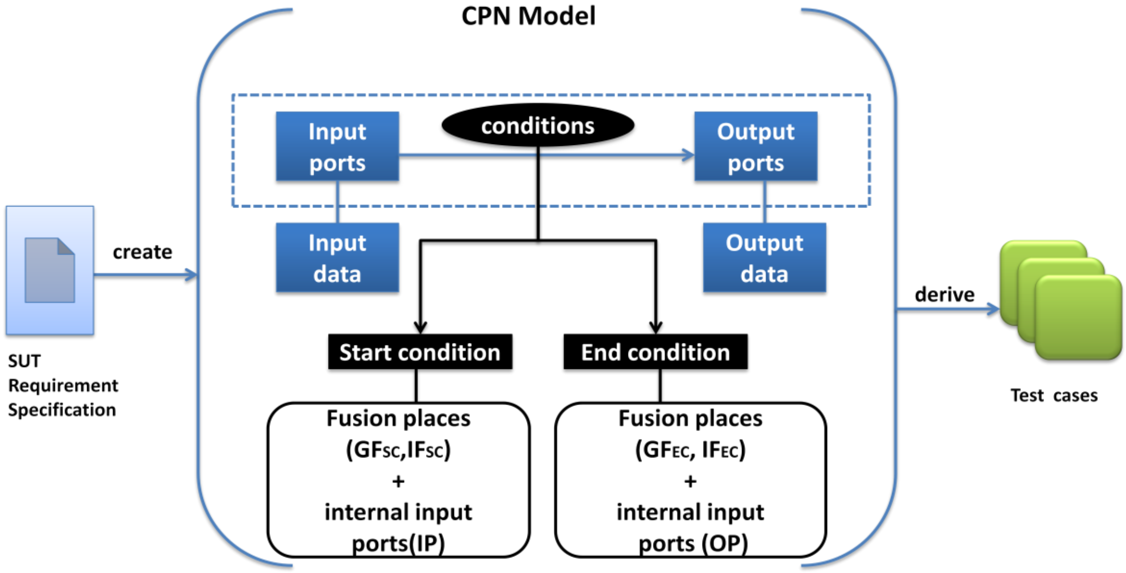


Figure 14 CPN Approach Overview

4.10 Finite State Machine (FSM)

Finite state machine is used to model the SUT behavior. According to figure 15, finite state model contains three parts: finite set of inputs, state transitions and finite set of responses [WAE+11]. Inputs represent the input stimuli. Transitions are the conditions that cause from one state to another state. The responses indicate the system responses for corresponding input stimuli.

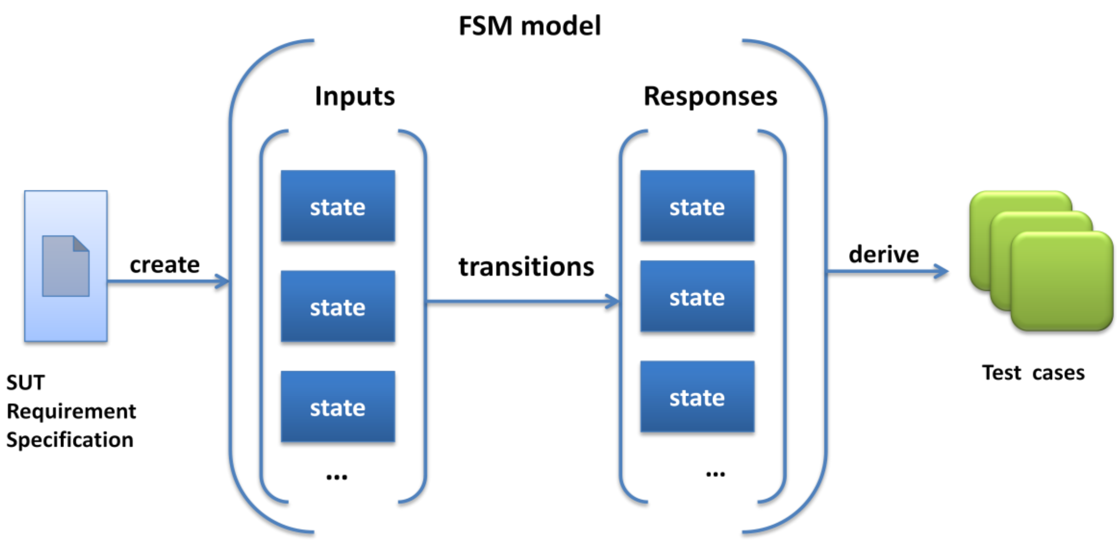


Figure 15 Finite State Machine Approach Overview

5. Case Study

This section provides the description of two running examples in the automotive domain, one represents discrete signal processing embedded system and the other one represents continuous signal processing embedded system. Their functional requirements are enclosed in Appendix A and B respectively. In this section, the previously described MBT approaches were applied to these two examples.

The applying procedures of those MBT methods with two simplified system cases are shown in section 5.3.

5.1 Seat-Belt Reminder System

The Seat-Belt Reminder System (SBRS) is used to remind the passengers when they are not fastened. The reminder generates a gong alert according to the driver seat-belt buckle status under different conditions. The main function of this system is to process the input data and to present the result as a gong sound. In this case, the SBRS collects input data from the engine, driver seat-belt buckle sensor and wheels: Vehicle front left wheel (Vwfl), Vehicle front right wheel (Vwfr), Vehicle rear left wheel (Vwrl), and Vehicle rear right wheel (Vwrr), speed sensors. The sign(x) indicates the car wheel's moving direction, i.e. +1 means forward and -1 means backward. The count (sign(x)) displays the car's moving direction. In the specified specification, four situations are considered:

- Count (sign(x))>= (+3) means that the car is moving forward
- Count (sign(x)) <= (-3) means the car is moving backward.
- Count(Sign(Vwfl)+sign(Vwfr)+sign(Vwrl)+sign(Vwrr))=(-2) means the car is moving backward towed by other vehicle
- Count(sign(Vwfl)+sign(Vwfr)+sign(Vwrl)+sign(Vwrr))=(+2) means the car is moving forward towed by other vehicle

5.2 Collision Detection System

The Collision Detection System (CDS) consists of a sensor that is placed in front of the vehicle and a reminder which is shown in figure 16. The sensor detects the distance with the front car, and the reminder is used to warn the driver to avoid the crash with front car. The CDS collects input data from the front sensor and wheels speed sensors.

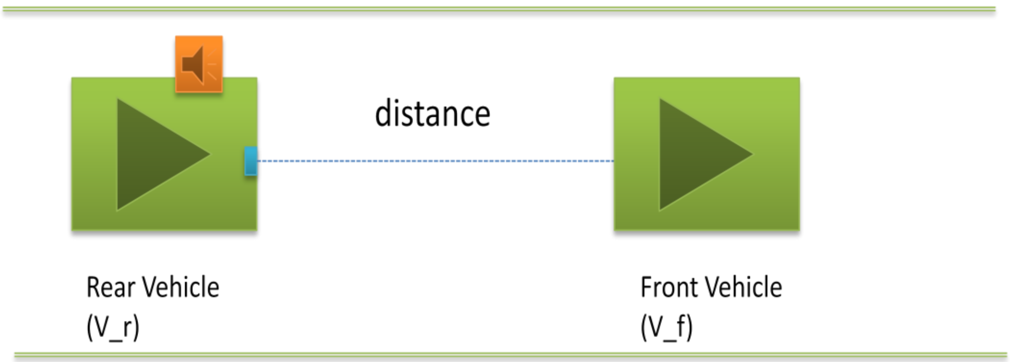


Figure 16 Collision Detection System Overview

The main function of this system is to process the input data to provide a predicted trend of the car's driving safety situation in next time points and to present the result as a warning sound to caution the driver to take actions from an unsafe situation to a safe situation.

5.2.1 Assumptions

The CDS example that defined in the specification is used for the academic research purpose only instead of practical implementation. Therefore, the following assumptions are made as follows:

- The two vehicles are moving forward toward the same direction and one vehicle drives after another one straightly, see figure 16.
- The front sensor can detect the relative distance with the front vehicle perfectly without deviation
- The vehicle wheel speed sensors can detect the velocity perfectly without deviation
- Reaction time for the driver to take actions during emergency situation is 1 second
- The deceleration for the vehicle is $7\frac{m}{s^2}$
- The coefficients are chosen arbitrarily for the sake of simplicity
- All the values involved are ideal and no uncertainties are considered

5.2.2 Operating Principle and Algorithm

The CDS uses the 3 latest time points' relative distance d between the front and the rear vehicles, and their velocities, i.e. V_r and V_f, information, to predict the next 3 time points' trend of car's driving safety situation. In order to be more understandable, $\{t_{n-2}, t_{n-1}, t_n, t_{n+1}, t_{n+2}, t_{n+3}\}$ is used for representing the time points in the following sections, t_{n-2} , t_{n-1} are latest time points, t_n is the current time point and $t_{n+1}, t_{n+2}, t_{n+3}$ are next future time points. The entire simplified algorithm works in the following steps:

1. Obtain the relative distance d and V_r of the t_{n-2},, t_{n-1}, t_n
2. Obtain the TTC ,$\Delta\ TTC$, tp_{crash} , t_{brake} , $tp_{braking}$ and $tp_{warning}$ (see figure 17) by applying related formulas, shown in below formulas section, respectively.

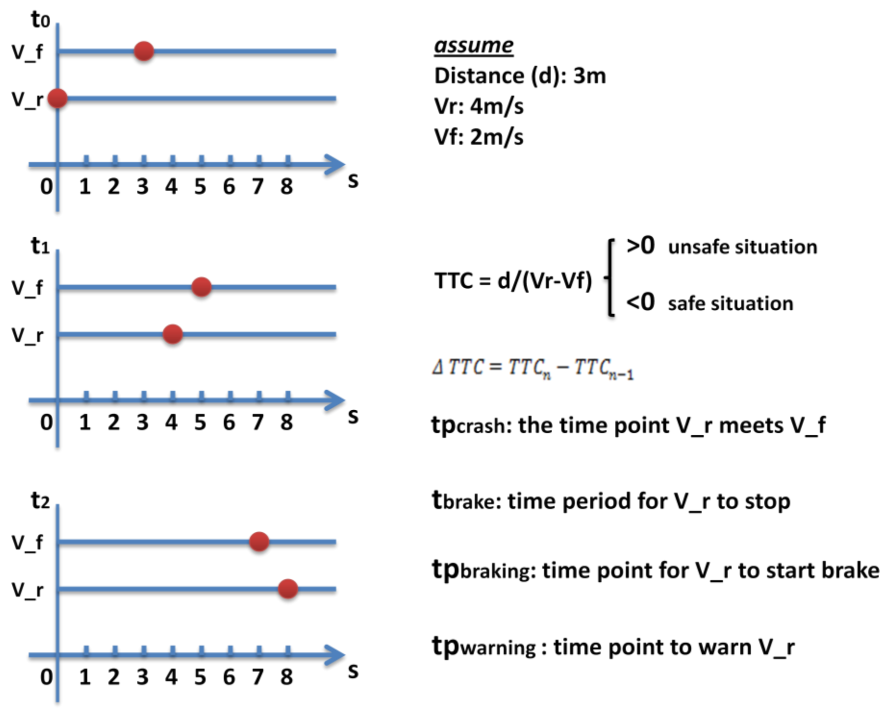


Figure 17 CDS definition terms

3. Calculate $\varDelta\, TTC_{pre}$ of t_n
4. Predict t_{n+1}'s TTC_{pre} , $t_{brake_{pre}}$, $tp_{braking_{pre}}$ and $tp_{warning_{pre}}$
5. Repeat step 3 and 4 until get all the required information of t_{n+2} and t_{n+3}
6. Check TTC_{pre} at different time points, e.g. $TTC_{pre_{tn+1}}$ means TTC_{pre} at time point t_{n+1}. And then compare the corresponding $t_{crash_{pre}}$of with the relevant time point. The detailed procedures are shown in figure 18

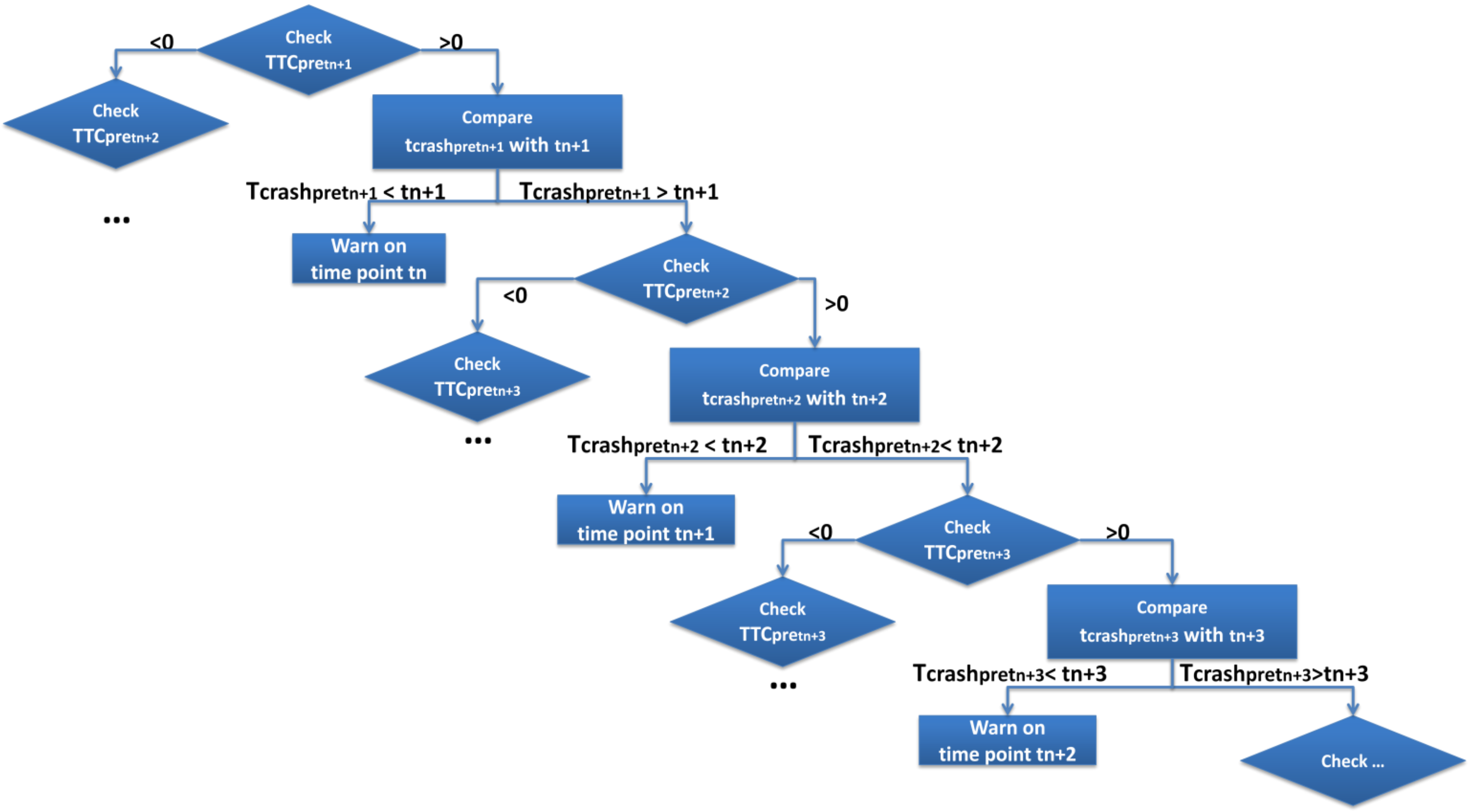


Figure 18 CDS Algorithm Diagram

5.2.3 Formulas

- $TTC = \frac{d}{V_r - V_f}$ (<0 : safe situation ; >0: unsafe situation)
- $\varDelta\, TTC = TTC_n - TTC_{n-1}$
- $TTC_{pre} = \ (0.5 * (\Delta TTC_{t_n} - \Delta TTC_{t_{n-1}}) + 0.375 * (\Delta TTC_{t_{n-1}} - \Delta\, TTC_{t_{n-2}}) + 0.125 * (\Delta TTC_{t_{n-2}} - \Delta TTC_{t_{n-3}}\ )\ ) + TTC$
- $\varDelta\, TTC_{pre} = \left(0.5 * \left(\Delta TTC_{t_n} - \Delta TTC_{t_{n-1}}\right) + 0.375 * \left(\Delta TTC_{t_{n-1}} - \Delta\, TTC_{t_{n-2}}\right) + 0.125 * \right.$ $\varDelta TTCtn{-}2{-}\varDelta TTCtn{-}3{+}\varDelta\, TTC$

(Note: 0.5, 0.375 and 0.125 are probability distribution, and the sum of them is 1. The probability distribution here is used for the example only. The latest time point gets the highest weight, i.e. 0.5, and the older time point gets the weight followed by decreasing 0.125)

- V_{pre} = (0.5*(V_n – V_{n-1})+0.375*(V_{n-1}– V_{n-2})+0.125*(V_{n-2}– V_{n-3})) + V_n
- $t_{brake} = \frac{V}{a}$ (a: acceleration)
- $tp_{crash} = TTC + t_n$
- $tp_{crash_{pre}} = TTC_{pre} + t_n$
- $tp_{braking} = tp_{crash} - t_{brake}$
- $tp_{warning} = tp_{braking} - t_{reaction}$
- $tp_{warning_{pre}} = tp_{braking_{pre}} - t_{reaction}$

5.3 MBT Methods Applying Descriptions

By following the descriptions in section4, these MBT methods were applied to these two simplified systems examples. In order to show how these MBT methods actually works, this section provides the four methods applying description for seat-belt reminder system as an example. The remainder methods were not applied with these two cases, the reasons are stated in section 6.

Sequence Based Specification

1. Define input stimuli from the Seat-Belt Reminder System (SBRS) functional requirements specification. The defined input stimuli were shown in table 4.

Stimulus	Description
CO	Car is on
CF	Car is off
F	Car is moving forward
B	Car is moving backward
FT	Car is moving forward by towed
BT	Car is moving backward by towed
DO	Driver seat-belt is on
DF	Driver seat-belt is off
SF	Detected speed >= 4m/s
SS	Detected speed <4m/s
DL	Duration >=5s
DS	Duration <5s

Table 4 SBRS System Input Stimuli

2. Combine the above stimuli in sequences by length. According to the SBRS system functional requirements specification, the system responses rely on the combination of several input stimuli, hence, the combination of input stimulus was be treated as input stimuli sequences in length 1, e.g. (CO,F,DO,SF,DL).
3. Capture the corresponding system responses for each input stimuli sequence and respective linked requirements. The input stimuli sequences without linked requirements marked as missing requirements.
4. Form the modeling table based on the length of input stimuli sequences, there were sixty-four input stimuli sequences defined when the length equals to 1 and only 2 input stimuli

sequences can be extended. Those 2 input stimuli sequences were extended with sixty-four input stimuli sequences respectively.

5. The modeling process stopped at length equals to 2 since there were no input stimuli sequences can be extended anymore.
6. Derive test cases by using the table when input stimuli sequences in length 2.

Classification Tree

1. Define expected input aspect and output aspect. The expected input aspect contains five classifications: car status, car moving direction, driver seat-belt, detected speed and duration. Car status partitions into on and off. Car moving direction divides into forward, backward, forward by towed and backward by towed. Driver seat-belt includes on and off. Detected speed contains two classes: greater than or equal to 4 meters per minute and less than 4 meters per minute. Duration partitions into two classes: greater or equal than 5 seconds and less than 5 seconds. Expected output contains gong on and gong off.
2. Combine the impartible classes of expected input and output as combination table.
3. Derive test cases by following test cases determination criteria.

Finite State Machine

1. Define input states. $State_{input}$ = {CS,MD,DSBS,DS,DU}, where CS means car status, MD stands for moving direction, DSBS means driver seat-belt status, DS represents detected speed and DU means duration. $state_{response}$= {GO,GF}, where GO means gong on and GF means gong off.
2. Capture the transitions from the functional requirements specification.
3. Link the input states and response states by corresponding transitions.
4. Derive test cases from the completed state diagram by finding complete paths that start from initial state to the destination state.

Event Sequence Graph

1. Capture expected behavior of SBRS system from the requirements specification, i.e. SBRS system presents a gong sound based on different conditions.
2. Define input stimuli events and system response events.
   $Event_{input}$={CO,CF,F,B,FT,BT,DO,DF,SF,SS,DL,DS}, description please see table 4.
   $Event_{response}$={GO,GF}, where GO stands for gong on and GF stands for gong off.
3. Conduct ESG graph by linking the input stimuli events to system response events using arrows based on the SBRS functional requirements specification.
4. Obtain the CES based test cases from the ESG graph.
5. Form ESG inversion graph by inverting the ESG graph.
6. Obtain the FCES from the ESG inversion graph. As the FCESs here only represent the unexpected input stimuli, the system responses are not known in SBRS functional requirements specification. The FCES based test cases could not be derived. Hence, the modeling process stopped.

6. Results

This section provides the results that came out by applying extracted Model Based Testing (MBT) approaches with two running examples. It includes two sub parts, one illustrates the results from the applied MBT approaches, and the other part states the reasons that why the remainder MBT approaches was not applied.

Applied MBT Approaches

There are five criteria that used to demonstrate results for approach.

a) *No. of test cases*: This is used to indicate that how many test cases are generated after applying the approach.
b) *Find missing requirements*: This shows the missing requirements in the defined software specification. The missing requirements are defined if there is no system response for the given input stimuli.
c) *Requirements coverage*: This shows that the requirement coverage status by applying the specific approach.
d) *Advantage*: This shows the benefit obtained after performing the specific approach.
e) *Disadvantage*: This illustrates the drawback obtained after applying the specific approach.

- **Sequence Based Specification**

Applied example	SBRS	CDS
No. of test cases	128	512
Finding missing requirements	4	7
Requirements coverage	All	All

Advantage:

- Covered all the requirements
- Discovered the missing requirements
- Easy to manipulate, even for the beginners, if the input stimuli are defined well.
- Provide requirements traceability, every stimuli sequence should have a respective requirement's support, which helps to find missing requirements.
- Provide multiple uses, for requirement validating, or derive test cases.

Disadvantage:

- The tester should understand the system requirements very well to define input stimuli, the input stimulus is the foundation of the following steps, the wrong defining will cause the later mistake.
- Not easy to manage the big table for large systems that have many requirements if there is no help from tool.
- A little time-consuming when extend the extendable stimuli.
- It is a challenge to combine many inputs as stimulus, especially for the system that has many inputs, e.g. CDS.

SBRS missing requirements
1) Car is on, and moving forward, the driver seat-belt is off, and the detected speed is >=4m/s, and the duration <5s, the gong should off
2) Car is on, and moving forward, the driver seat-belt is off, and the detected speed is <4m/s, and the duration >=5s, the gong should off
3) Car is on, and moving backward, the driver seat-belt is off, and the detected speed is >=4m/s, and the duration <5s, the gong should off
4) Car is on, and moving backward, the driver seat-belt is off, and the detected speed is <4m/s, and the duration >=5s, the gong should off
CDS missing requirements
1) When tn’s TTC<0 and tn+1’s TTC_pre<0 and tn+2’s TTC_pre<0 and tn+3’s TTC_pre>0 and tn+3’s t_crash_pre>tn+3, the gong should be off
2) When tn’s TTC<0 and tn+1’s TTC_pre<0 and tn+2’s TTC_pre>0 and tn+2’s t_crash_pre>tn+2 and tn+3’s TTC_pre<0, the gong should be off
3) When tn’s TTC<0 and tn+1’s TTC_pre<0 and tn+2’s TTC_pre>0 and tn+2’s t_crash_pre>tn+2 and tn+3’s TTC_pre>0 and tn+3’s t_crash_pre>tn+3 , the gong should be off
4) When tn’s TTC<0 and tn+1’s TTC_pre>0 and tn+1’s t_crash_pre>tn+1 and tn+2’s TTC_pre<0 and tn+3’s TTC_pre>0 and tn+3’s t_crash_pre>tn+3 , the gong should be off
5) When tn’s TTC>0 and tn+1’s TTC_pre<0 and tn+2’s TTC_pre>0 and tn+2’s t_crash_pre>tn+2 and tn+3’s TTC_pre>0 and tn+3’s t_crash_pre>tn+3 , the gong should be off
6) When tn’s TTC>0 and tn+1’s TTC_pre>0 and tn+1’s t_crash_pre>tn+1 and tn+2’s TTC_pre<0 and tn+3’s TTC_pre>0 and tn+3’s t_crash_pre>tn+3 , the gong should be off
7) When tn’s TTC>0 and tn+1’s TTC_pre>0 and tn+1’s t_crash_pre>tn+1 and tn+2’s TTC_pre>0 and tn+2’s t_crash_pre>tn+2 and tn+3’s TTC_pre<0 , the gong should be off

Table 5 Missing Requirements

- ## Event Sequence Graph

Applied example	SBRS	CDS
No. of test cases	/	/
Finding missing requirements	None	None
Requirement coverage	All	All

Advantage:

- Helps to find comprehensive test cases, because it covers expected and unexpected behavior.
- It is easy to have the FCES when CES is defined.
- It is good at finding unexpected behavior of system and also providing solution to handle.

Disadvantage:

- So many similar terminologies, like EP, ES, CES, FCES etc, it is easy to be confused in the beginning.
- The completed graph looks so complex, especially the relation lines cross each other, which might cause vision problem for big system with complicated requirements.

- It is not easy for future modification.
- It is real confused to find FCES test cases manually, since all the inventions are really complex.
- It cannot guarantee detect all the functional faults. Because the succeed test should be checked that whether the expected results obtained.
- It is quite hard to obtain the test cases manually without the tool help.

- **Classification Tree**

Applied example	SBRS	CDS
No. of test cases	34	22
Finding missing requirements	None	None
Requirement coverage	All	All

Advantage:

- Provide minimum and maximum criteria, which helps to obtain reachable number of test cases
- Easy to modify in the combination table
- Entire tree is easy to understand

Disadvantage

- Need rich experience and creativity to follow the maximum criteria

- **Finite State Machine**

Applied example	SBRS	CDS
No. of test cases	8	20
Finding missing requirements	None	None
Requirement coverage	All	All

Advantage:

- Easy to use for modeling system behavior
- Can be integrated with other methods easily

Disadvantage

- Can't guarantee to detect all the functional faults

Not Applied MBT Approaches

The following approaches were not applied with running examples, the corresponding reasons are stated.

- UML/OCL: this approach is presented to model the behavior of the SUT environment rather than the behavior of the SUT. This thesis works on studying modeling approach for modeling SUT behavior.
- Stateflow Automata: this technique is proposed to test the feature interaction. In the defined running examples, each example has one feature only. It is not proper to apply this technique.
- Fault Tree Analyses: this approach focuses on failure mode analysis, which is not defined in the running example specification.

- Markov Chain: this approach needs system internal structure knowledge. This work focuses on black box testing approaches that do not consider system internal structure.
- Coloured Petri Net: this approach should be applied by knowing the internal structure of the SUT.
- CoFI : this approach specifies four classes of finite state machine: (1) normal behavior, (2) specified exceptions, (3) inopportune inputs and (4) hardware faults. This evaluation only considers the class (1), as the provided running example specification is defined under assumption without exception and unexpected inputs consideration. And there is no dependency on hardware in this study as well. Hence, the evaluation result is the same as finite state machine.

In Applied MBT Approaches subsection, four methods are applied with running examples. Sequence Based Specification is the only method that found the missing requirements of the software specification because it provides requirements traceability. There is no exact number of test cases derived for event sequence graph, because due to the specification limitation, i.e. only contains functional requirements, there is no response for unexpected input stimuli. Hence, the test cases cannot be derived successfully.

According to the analysis of the results, the following considerations are conducted:

- Sequence based specification can be considered as the basic behavior model that used to integrated with fault based analysis method, e.g. fault tree analyses. And sequence based specification method is strongly recommend as requirements specification validation method.
- Sequence based specification and event sequence based method are recommend for beginners, because they are intuitive to use without requiring much expert knowledge, and also they provide guidance during modeling process.
- Classification tree is pretty good for modeling small size system. However, this method needs experience and creativity to derive test cases according to its maximum criteria.
- Finite state machine approaches are used widely in model based testing by integrating with other approaches, e.g. CoFI, Markov chain and fault tree analyses.
- Event sequence graph is recommended to test fault mode of system under test.

7. Conclusion and Outlook

The intention of this thesis is to find the available Model-Based Testing (MBT) approaches for validating automotive embedded systems from publications and to provide the advantage and disadvantage of those approaches by evaluating such approaches with two running examples.

This work presents the findings from the systematic literature review. 5 search queries were applied in 8 digital libraries. 10 MBT approaches that used for automotive embedded systems were obtained. Those MBT approaches principles are displayed with corresponding graphical demonstration.

The study provides functional requirements of two conducted safety-critical functions in the automotive domain as running examples. One is called Seat-Belt Reminder System that represents discrete signal processing embedded systems. The other one is a representation of continuous signal processing embedded system called Collision Detection System. As these two running examples are defined for academic research instead of practical implementation, their specified requirements were defined under ideal assumptions. For instance, the involved parameters are simplified. However, their functional requirements can be considered as suggestive reference. This research also provides the evaluation results after applying such approaches with two running examples. The advantages and disadvantages are presented, which can be helpful in selecting proper approaches for validating automotive embedded systems.

Due to the scope limitation of the thesis, this work focused on the early stage of model based testing, i.e. manually creating models from system requirements specification and deriving abstract test cases. The future work could be to conduct research on transforming the abstract test cases into executable test scripts with the help of tools. As the present study applied and evaluated MBT approaches on fictive simplified system specifications, other future work could include doing research on evaluating those MBT approaches on real systems.

References

[ABJ+10] Aichernig, B. K., Brandl, H., Jobstl, E. and Krenn, W. (2010), "Model-Based Mutation Testing of Hybrid Systems", Proceedings of the 8th International Conference on Formal Methods for Components and Objects 2010, Berlin, Heidelberg, 2010.

[AMV+06] Ambrosio, A. M., Martins, E., Vijaykumar, N. L. and Carvalho, S. V. (2006), "A conformance testing process for space applications software services", Journal of J Aerosp Comput Inf Commun (JACIC), USA 3(4): 146-158.

[AUT12a] AUTOSAR, found at website http://en.wikipedia.org/wiki/AUTOSAR [accessed Sep 29th 2012].

[AUT12b] AUTOSAR, found at website http://www.autosar.org/ [accessed Sep 29th 2012].

[BHK09] Belli, F., Hollmann, A. and Kleinselbeck, M. (2009), "A Graph-Model-Based Testing Method Compared with the Classification Tree Method for Test Case Generation", Proceedings of the 3rd IEEE International Conference on Secure Software Integration and Reliability Improvement 2009, Washington, DC, USA, 2009.

[BNB+05] Belli, F., Nissanke, N., Budnik, C. J. and Mathur, A.(2005), "Test Generation Using Event Sequence Graph", Technical Reports and Working Papers, University of Paderborn, Insititute for Electrical Engineering and Information Technology, USA, 2005.

[BR10] Brunnlieb, M. and Rauch, T. (2010), "Sequence-Based Software Specification".

[BS12] Berger, C. and Siegl, S. (2012), "Constructive Requirements Modeling – More Reliable Implementations in a Shorter Time", Proceedings of the Conference Automotive – Safety & Security 2012, Lecture Notes in Informatics (LNI), 2012.

[CAO+08] Cartaxo, E.G., Andrade, W.L., Oliveira-Neto, F.G. and Machado, P.D.L. (2008), "LTS-BT: A Tool to Generate and Select Functional Test Cases for Embedded Systems", Proceedings of the ACM Symposium on Applied Computing 2008, New York, USA, 2008.

[CHG12] Caliebe, P., Herpel, T., and German, R. (2012), "Dependency-Based Test Case Selection and Prioritization in Embedded Systems", Proceedings of the IEEE Fifth International Conference on Software Testing, Verification and Validation 2012, Germany, 2012.

[CP07] Carter, J.M. and Poore, J.H. (2007), "Sequence-based Specification of Feedback Control Systems in Simulink", Proceedings of Conference of the Center for Advanced Studies on Collaborative Research 2007, Riverton,NJ,USA,2007.

[CSV10] Cristia, M., Santiago, V. and Vijaykumar, N.L. (2010), "On Comparing and Complementing Two MBT Approaches", Proceedings of Test Workshop (LATW) 2010 11th Latin American, March 28-31, 2010.

[DL11] Davies, M.D. and Limes, G. (2011), "Finding System-level Failures in Flight-Critical Software Systems", Proceedings of 30th IEEE/AIAA Digital Avionics Systems Conference (DASC), CA, USA, October 16-20, 2011.

[DSV+07] Dias-Neto, A.C., Subramanyan, R., Vieira, M. and Travassos, G.H. (2007), "A Survey on Model-based Testing Approaches: A Systematic Review", Proceedings of the 1st ACM International Workshop on Empirical Assessment of Software Engineering Languages and Technologies: held in conjunction with the 22nd IEEE/ACM International Conference on Automated Software Engineering (ASE) 2007, New York, NY, USA, 2007.

[DT08] Dias-Neto, A.C. and Travassos, G.H. (2008), "Supporting the Selection of Model-based Testing Approaches for Software Projects", Proceedings of the 3rd international workshop on Automation of Software Test, New York, NY, USA, 2008.

[FGM+10] Ferrari, A., Grasso, D., Magnani, G., Fantechi, A. and Tempestini, M. (2010), "The Metro Rio ATP Case Study", Proceedings of the 15th International Conference on Formal Methods for Industrial Critical Systems 2010, Berlin, Heidelberg, 2010.

[GG93] Grochtmann, M. and Grimm, K. (1993), "Classification Trees for Partition Testing", Journal of Software Testing, Verification and Reliability, Vol. 3,No.2, pp.63-82.

[HKO06] Hartman, A., Katara, M. and Olvovsky, S. (2006), "Choosing a Test Modeling Language: A Survey", Proceedings of the 2nd international Haifa Verification Conference on Hardware and Software, Verification and Testing, Berlin, Heidelberg, 2006.

[ISO12] ISO 26262, found at website http://en.wikipedia.org/wiki/ISO_26262 [accessed Sep 29th 2012].

[JB11] Junior, G.D. and Bonifacio, A.L. (2011), "A Tool to Support Model-Based Testing Activities", Proceedings of Computing System Engineering (SBESC) 2011, Brazil, November 7-11, 2011.

[KH07] Kollmann, M. and Hon, Y.M. (2007),"Generating Scenarios by Multi-Object Checking", Proceedings of the 3rd Electronic Notes in Theoretical Computer Science Workshop on Model Based Testing 2007, Germany, August 2007.

[KHE11] Kloos, J., Hussain, T. and Eschbach, R. (2011), "Risk-based Testing of Safety-Critical Embedded Systems Driven by Fault Tree Analysis", Proceedings of 4th IEEE International Conference on Software Testing, Verification and Validation Workshops 2011, Washington, DC,USA.

[LBL+11] Lasalle, J., Bouquet, F., Legeard, B. and Peureux, F. (2011), "SysML to UML Model Transformation for Test Generation purpose", Newsletter of Software Engineering Notes, Vol.36, No.1, pp.1-8.

[LG10] Lochau, M. and Goltz, U. (2010), "Feature Interaction Aware Test Case Generation for Embedded Control Systems", Journal of Electronic Notes in Theoretical Computer Science (ENTCS), Vol.264, No.3, pp37-52.

[LPG11] Lasalle, J., Peureux, F. and Guillet, J. (2011), "Automatic Test Concretization to Supply End-to-End MBT for Automotive Mechatronic Systems", Proceedings of the 1st International Workshop on End-to-End Test Script Engineering 2011, New York, USA, 2011.

[LPW11] Lyenghar, P., Pulvermueller, E. and Westerkamp, C. (2011), "Towards Model-Based Test Automation for Embedded Systems Using UML and UTP", Proceedings of 16th IEEE Conference on Emerging Technologies & Factory Automation (ETFA) 2011, Germany, September 5-9, 2011.

[LWW10] Lindlar, F., Windisch, A. and Wegener, J. (2010), "Integrating Model-Based Testing with Evolutionary Functional Testing", Proceedings of the 3rd International Software Testing, Verification and Validation Workshops (ICSTW) 2010, Berlin, Germany, April 6-10, 2010.

[MTL10] Malik, Q.A., Truscan, D. and Lilius, J. (2010), "Using UML Models and Formal Verification in Model-Based Testing", Proceedings of the 17th IEEE International Conference and Workshops on the Engineering of Computer-Based Systems 2010, Washington, DC, USA, 2010.

[MWF+11] Mitsching, R., Weise, C., Franke, D., Gerlitz, T. and Kowalewski, S. (2011),"Coping with Complexity of Testing Models for Real-Time Embedded Systems", Proceedings of the 5th International Conference on Secure Software Integration and Reliability Improvement –Companion 2011, Washington, DC, USA, 2011.

[NE08] Nakao, H. and Eschbach, R. (2008), "Strategic Usage of Test Case Generation by Combining Two Test Case Generation Approaches", Proceedings of the 2nd International Conference on Secure System Integration and Reliability Improvement 2008, Washington, DC, USA, 2008.

[Pel08] Peleska, J. (2008), "A Unified Approach to Abstract Interpretation, Formal Verification and Testing of C/C++ Modules", Proceedings of the 5th International Colloquium on Theoretical Aspects of Computing 2008, Berlin, Heidelberg, 2008.

[PFH+06] Pfaller, C., Fleischmann, A., Hartmann, J., Rappl, M., Rittmann, S., and Wild, D.(2006), "On the integration of Design and Test – A Model-Based Approach for Embedded Systems ", Proceedings of the 2006 international workshop on Automation of software test, New York ,USA,2006.

[PVA+12] Pontes, R.P., Veras, P.C., Ambrosio, A.M. and Villani, E.(2012), "Contributions of model checking and CoFI methodology to the development of space embedded software", Journal of Empirical Software Engineering, pp.1-30.

[Rob11] Roberts, G. (2011), "GERMANY: ESP now mandatory in Europe", found at website http://www.just-auto.com/news/esp-now-mandatory-in-europe_id117266.aspx [accessed Sep 29th 2012].

[SHJ11] Schlick, R., Herzner, W. and Jobstl, E. (2011), "Fault-Based Generation of Test Cases from UML-Models – Approach and Some Experiences", Proceedings of the 30th International Conference on Computer Safety, Reliability and Security, Berlin, Heidelberg, 2011.

[SSM07] Software Engineering Group, School of Computer Science and Mathematics, Keele Univeristy, and Department of Computer Science, University of Durham "Guidelines for performing Systematic Literature Review in Software Engineering", EBSE Technical Report, EBSE-2007-01, UK, 2007.

[TBL+09] Tamisier, T., Bouzite, H., Louis, C., Gaffinet, Y. and Feltz, F. (2009), "Model Based Testing for Horizontal and Vertical Collaboration in Embedded Systems

Development", Proceedings of the 6th International Conference on Cooperative Design, Visualization, and Engineering 2009, Berlin, Heidelberg, 2009.

[Tur10] Turner, M. (2010), "Digital Libraries and Search Engines for Software Engineering Research: An Overview", Keele University, UK.

[UL06] Utting, M. and Legeard, B. (2006), Practical Model-Based Testing: A Tools Approach, San Francisco: Morgan Kaufmann.

[WAE+11] Wu-Hen-Chang, A., Adamis, G., Eros, L., Kovacs, G. and Csondes, T. (2011), "A New Approach in Model-Based Testing: Designing Test Models in TTCN-3", Proceedings of the 15th International Conference on Integrating System and Software Modeling, Berlin, Heidelberg, 2011.

[YXD09] Yu, G., Xu, Z.W. and Du, J.W. (2009), "An Approach for Automated Safety Testing of Safety-Critical Software System based on Safety Requirements", Proceedings of the International Forum on Information Technology and Applications 2009,Washington, DC, USA, May 15-17, 2009.

[Zan08] Zander-Nowicka, J. (2008), "Model-based Testing of Real-Time Embedded Systems in the Automotive Domain", Master Thesis, Technical University Berlin, Germany.

[ZZZ+10] Zhao, X., Zhang, Y., Zheng, W., Tang, T. and Mu, R. (2010), "Modeling and Design of the Formal Approach for Generating Test Sequences of ETCS level 2 based on the CPN", Proceedings of 12th International Conference on Computer System Design and Operation in Railways and Other Transit Systems 2010, Beijing, China, August 31 – September 2 , 2010 .

Appendices

Appendix A --- Seat-Belt Reminder System (SBRS) Functional Requirements

This section provides the gong functionality of seat-belt reminder system. The gong functionality informs the driver if he/she is unbuckled. Table 6 demonstrates how gong sounds are performed based on specific conditions, as well as, detail description in below.

Gong sound	Car	Sign(x)				Count(sign(x))		Driver seat-belt	Avg (Detected Speed)	Duration
		Sign (Vwfl)	Sign (Vwfr)	Sign (Vwrl)	Sign (Vwrr)	+	-			
On	On	+1	+1	+1	+1	4		Off	Speed > = 4m/s	t>=5s
		+1	+1	+1	-1	3				
		+1	+1	-1	+1	3				
		+1	-1	+1	+1	3				
		-1	+1	+1	+1	3				
		-1	-1	-1	-1		4			
		-1	-1	-1	+1		3			
		-1	-1	+1	-1		3			
		-1	+1	-1	-1		3			
		+1	-1	-1	-1		3			
Off	Off	/	/	/	/	/		/	/	/
	On	/	/	/	/	/		On	/	/
		+1	+1	+1	+1	4		Off	Speed < 4m/s	t<5s
		+1	+1	+1	-1	3				
		+1	+1	-1	+1	3				
		+1	-1	+1	+1	3				
		-1	+1	+1	+1	3				
		-1	-1	-1	-1		4			
		-1	-1	-1	+1		3			
		-1	-1	+1	-1		3			
		-1	+1	-1	-1		3			
		+1	-1	-1	-1		3			
		0	0	+1	+1	2			/	/
		-1	-1	0	0		2			
		0	+1	0	+1	2				
		0	+1	+1	0	2				
		0	-1	0	-1		2			
		0	-1	-1	0		2			
		0	0	-1	-1		2			
		+1	+1	0	0	2				
		+1	0	+1	0	2				
		+1	0	0	+1	2				
		-1	0	-1	0		2			
		-1	0	0	-1		2			

Table 6 SBRS Functional Requirements

A gong sound shall be on to remind the driver based on the following different conditions:

- The car is on **and** the count(sign(x))>=(+3)**and** the drive seat-belt is off **and** detected speed is equal or greater than 4m/s **and** the speed duration lasts for 5 seconds.
- The car is on **and** the count(sign(x))<=(-3) **and** the drive seat-belt is off **and** detected speed is equal or greater than 4 m/s **and** speed duration lasts for 5 seconds.

A gong sound shall be off based on the following different conditions:

- The car is off
- The car is on **and** driver seat-belt is on
- The car is on **and** count (sign(x)) <= (-3) **and** detected speed less than 4m/s **and** speed duration lasts for 5 seconds.
- The car is on **and** count (sign(x))>= (+3) **and** detected speed less than 4m/s **and** speed duration lasts for 5 seconds.
- The car is on **and** car is moving backward towed by other vehicle , which the Count(Sign(Vwfl)+sign(Vwfr)+sign(Vwrl)+sign(Vwrr))=(-2)
- The car is on **and** car is moving forward towed by other vehicle, which Count(Sign(Vwfl)+sign(Vwfr)+sign(Vwrl)+sign(Vwrr))=(+2)

Appendix B --- Collision Detection System (CDS) Functional Requirements

Table 7 provides the functional requirements of CDS, and it demonstrates how warning sound is performed based on specific conditions, as well as, detailed description in below.

voice warning sound		tn	tn+1	tn+2	tn+3
On (tn)	TTC	>0			
	TTC_{pre}		>0		
	$tp_{crash_{pre}}$		<tn+1		
	TTC	<0			
	TTC_{pre}		>0		
	$tp_{crash_{pre}}$		<tn+1		
On(tn+1)	TTC	>0			
	TTC_{pre}		>0	>0	
	$tp_{crash_{pre}}$		>tn+1	<tn+2	
	TTC	>0			
	TTC_{pre}		<0	>0	
	$tp_{crash_{pre}}$			<tn+2	
	TTC	<0			
	TTC_{pre}		>0	>0	
	$tp_{crash_{pre}}$		>tn+1	<tn+2	
	TTC	<0			
	TTC_{pre}		<0	>0	
	$tp_{crash_{pre}}$			<tn+2	
On(tn+2)	TTC	>0			
	TTC_{pre}		>0	>0	>0
	$tp_{crash_{pre}}$		>tn+1	>tn+2	<tn+3
	TTC	>0			
	TTC_{pre}		>0	<0	>0
	$tp_{crash_{pre}}$		>tn+1		<tn+3
	TTC	>0			
	TTC_{pre}		<0	<0	>0
	$tp_{crash_{pre}}$				<tn+3

	TTC	<0			
	TTC_{pre}		>0	>0	>0
	$tp_{crash_{pre}}$		>tn+1	>tn+2	<tn+3
	TTC	<0			
	TTC_{pre}		>0	<0	>0
	$tp_{crash_{pre}}$		>tn+1		<tn+3
	TTC	<0			
	TTC_{pre}		<0	>0	>0
	$tp_{crash_{pre}}$			>tn+2	<tn+3
	TTC	<0			
	TTC_{pre}		<0	<0	>0
	$tp_{crash_{pre}}$				<tn+3
Off	TTC	<0			
	TTC_{pre}		<0	<0	<0
	TTC	>0			
	TTC_{pre}		>0	>0	>0
	$tp_{crash_{pre}}$		>tn+1	>tn+2	>tn+3
	TTC	>0			
	TTC_{pre}		>0	<0	<0
	$tp_{crash_{pre}}$		>tn+1		
	TTC	>0			
	TTC_{pre}		<0	<0	<0
	TTC	>0			
	TTC_{pre}		<0	>0	<0
	$tp_{crash_{pre}}$			>tn+2	
	TTC	>0			
	TTC_{pre}		<0	<0	>0
	$tp_{crash_{pre}}$				>tn+3
	TTC	<0			
	TTC_{pre}		>0	<0	<0
	$tp_{crash_{pre}}$		>tn+1		

	TTC	<0			
	TTC_{pre}		>0	>0	<0
	$tp_{crash_{pre}}$		>tn+1	>tn+2	
	TTC	<0			
	TTC_{pre}		>0	>0	>0
	$tp_{crash_{pre}}$		>tn+1	>tn+2	>tn+3

Table 7 CDS Functional Requirements

<u>A warning sound shall be provided to remind the driver based on the following different conditions:</u>

The sound should be displayed on time point tn

- When tn's TTC>0 and tn+1's TTC_{pre}>0 and tn+1's $tp_{crash_{pre}}$<tn+1
- When tn's TTC<0 and tn+1's TTC_{pre}>0 and tn+1's $tp_{crash_{pre}}$<tn+1

The sound should be displayed on time point tn+1

- When tn's TTC>0 and tn+1's TTC_{pre}>0 and tn+1's $tp_{crash_{pre}}$>tn+1 and tn+2's TTC_{pre}>0 and tn+2's $tp_{crash_{pre}}$<tn+2
- When tn's TTC>0 and tn+1's TTC_{pre}<0 and tn+2's TTC_{pre}>0 and tn+2's $tp_{crash_{pre}}$<tn+2
- When tn's TTC<0 and tn+1's TTC_{pre}>0 and tn+1's $tp_{crash_{pre}}$>tn+1 and tn+2's TTC_{pre}>0 and tn+2's $tp_{crash_{pre}}$<tn+2
- When tn's TTC<0 and tn+1's TTC_{pre}<0 and tn+2's TTC_{pre}>0 and tn+2's $tp_{crash_{pre}}$<tn+2

The sound should be displayed on time point tn+2

- When tn's TTC>0 and tn+1's TTC_{pre}>0 and tn+1's $tp_{crash_{pre}}$>tn+1 and tn+2's TTC_{pre}>0 and tn+2's $tp_{crash_{pre}}$>tn+2 and tn+3's TTC_{pre}>0 and tn+3's $tp_{crash_{pre}}$<tn+3
- When tn's TTC>0 and tn+1's TTC_{pre}>0 and tn+1's $tp_{crash_{pre}}$>tn+1 and tn+2's TTC_{pre}<0 and tn+3's TTC_{pre}>0 and tn+3's $tp_{crash_{pre}}$<tn+3
- When tn's TTC>0 and tn+1's TTC_{pre}<0 and tn+2's TTC_{pre}<0 and tn+3's TTC_{pre}>0 and tn+3's $tp_{crash_{pre}}$<tn+3
- When tn's TTC<0 and tn+1's TTC_{pre}>0 and tn+1's $tp_{crash_{pre}}$>tn+1 and tn+2's TTC_{pre}>0 and tn+2's $tp_{crash_{pre}}$>tn+2 and tn+3's TTC_{pre}>0 and tn+3's $tp_{crash_{pre}}$<tn+3
- When tn's TTC<0 and tn+1's TTC_{pre}>0 and tn+1's $tp_{crash_{pre}}$>tn+1 and tn+2's TTC_{pre}<0 and tn+3's TTC_{pre}>0 and tn+3's $tp_{crash_{pre}}$<tn+3

- When tn's TTC<0 and tn+1's TTC_{pre}<0 and tn+2's TTC_{pre}>0 and tn+2's $tp_{crash_{pre}}$>tn+2 and tn+3's TTC_{pre}>0 and tn+3's $tp_{crash_{pre}}$<tn+3
- When tn's TTC<0 and tn+1's TTC_{pre}<0 and tn+2's TTC_{pre}<0 and tn+3's TTC_{pre}>0 and tn+3's $tp_{crash_{pre}}$<tn+3

A warning sound shall not be provided based on the following different conditions:

- When tn's TTC<0 and tn+1's TTC_{pre}<0 and tn+2's TTC_{pre}<0 and tn+3's TTC_{pre}<0
- When tn's TTC>0 and tn+1's TTC_{pre}>0 and tn+1's $tp_{crash_{pre}}$>tn+1 and tn+2's TTC_{pre}>0 and tn+2's $tp_{crash_{pre}}$>tn+2 and tn+3's TTC_{pre}>0 and tn+3's $tp_{crash_{pre}}$>tn+3
- When tn's TTC>0 and tn+1's TTC_{pre}>0 and tn+1's $tp_{crash_{pre}}$>tn+1 and tn+2's TTC_{pre}<0 and tn+3's TTC_{pre}<0
- When tn's TTC>0 and tn+1's TTC_{pre}<0 and tn+2's TTC_{pre}<0 and tn+3's TTC_{pre}<0
- When tn's TTC>0 and tn+1's TTC_{pre}<0 and tn+2's TTC_{pre}>0 and tn+2's $tp_{crash_{pre}}$>tn+2 and tn+3's TTC_{pre}<0
- When tn's TTC>0 and tn+1's TTC_{pre}<0 and tn+2's TTC_{pre}<0 and tn+3's TTC_{pre}>0 and tn+3's $tp_{crash_{pre}}$>tn+3
- When tn's TTC<0 and tn+1's TTC_{pre}>0 and tn+1's $tp_{crash_{pre}}$>tn+1 and tn+2's TTC_{pre}<0 and tn+3's TTC_{pre}<0
- When tn's TTC<0 and tn+1's TTC_{pre}>0 and tn+1's $tp_{crash_{pre}}$>tn+1 and tn+2's TTC_{pre}>0 and tn+2's $tp_{crash_{pre}}$>tn+2 and tn+3's TTC_{pre}<0
- When tn's TTC<0 and tn+1's TTC_{pre}>0 and tn+1's $tp_{crash_{pre}}$>tn+1 and tn+2's TTC_{pre}>0 and tn+2's $tp_{crash_{pre}}$>tn+2 and tn+3's TTC_{pre}>0 and tn+3's $tp_{crash_{pre}}$>tn+3

Appendix C --- Glossary

Term	Description
SBRS	Seat-Belt Reminder System
CDS	Collision Detection System
$\boldsymbol{V}$	vehicle velocity
$\boldsymbol{V_{pre}}$	predicted vehicle velocity
$\boldsymbol{V_f}$	the front vehicle velocity
$\boldsymbol{V_r}$	the rear vehicle velocity
$\boldsymbol{Vwfl}$	the vehicle front left wheel
$\boldsymbol{Vwfr}$	the vehicle front right wheel
$\boldsymbol{Vwrl}$	the vehicle rear left wheel
$\boldsymbol{Vwrr}$	the vehicle rear right wheel
$\boldsymbol{d}$	the relative distance between the front vehicle and the rear vehicle
$\boldsymbol{TTC}$	Time to Collision. It is used to distinguish the driving security status. The vehicle is in a safe situation if the value of TTC is negative, otherwise the opposite.
$\boldsymbol{TTC_{pre}}$	predicted TTC
$\boldsymbol{\Delta\, TTC}$	the difference between TTCs
$\boldsymbol{\Delta\, TTC_{pre}}$	predicted delta TTC
$\boldsymbol{t_{brake}}$	the time period for car to stop
$\boldsymbol{t_{brake_{pre}}}$	predicted t_{brake}
$\boldsymbol{tp_{braking}}$	time to start brake
$\boldsymbol{tp_{braking_{pre}}}$	predicted $tp_{braking}$
$\boldsymbol{tp_{crash}}$	time point to crash
$\boldsymbol{tp_{crash_{pre}}}$	predicted tp_{crash}
$\boldsymbol{tp_{warning}}$	time point to warn
$\boldsymbol{tp_{warning_{pre}}}$	tredicted $tp_{warning}$
$\boldsymbol{t_{reaction}}$	time for driver to react during emergency situation
x	detected signal of the vehicle wheel speed sensor