

Human-Centered Reliability Assessment and Condition Monitoring in Road Transportation Systems

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**Thesis submitted to the Faculty of Graduate and Postdoctoral Studies in partial
fulfillment of the requirements for the Doctorate of Philosophy degree in
Mechanical Engineering**

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Acknowledgments

I would like to express my deepest gratitude to my thesis supervisor, Professor Balbir. S. Dhillon, for his ceaseless and kind support, advice, and guidance.

My sincere thanks to my academic advisory committee Professor Dan S. Nesculescu and Professor Ming Liang for their input and comments which significantly contributed in the quality improvement of this thesis.

My special thanks and gratitude to the thesis examining committee including Professor Elsayed A. Elsayed, Professor Tofy Mussivand, Professor Dan S. Nesculescu, and Dr. Ahmad Jarde for accepting to serve in this committee and for their mastery comments.

My gratitude to the faculties and staff of the Mechanical Engineering Department and for all the wonderful years that I spent and great memories to be carried for the rest of my life.

My special thanks to Dr. Natalie Baddour, great chair of our department, who also served in my Comprehensive Exam Committee.

I also would like to thank whole heartedly my family and friends which without their continued support and encouragement this could not have happened.

Abstract

The risk analysis process involving information acquisition, modeling, analysis, and decision steps result in system design improvement. To allow an accurate and active system risk assessment in road transportation, this study identifies the contributing factors in reliability of road transportation systems and develops the systematic and stochastic methodologies and mathematical models. The developed models and methodologies aim to assess the reliability and risk of drivers interacting with the today's typical vehicles equipped with Advanced Drivers Assistance System (ADAS) and Passive Safety Systems (PSS) with any degree of complexity and availability of such systems. The research further examines and addresses the specific needs of such vulnerable users and perhaps risk to others on roads including older drivers, younger drivers and pedestrians. The research presents the conditions monitoring concepts as in-vehicle tools for live assessment of risk state of drivers built on the methodologies and models developed in the studies. The necessity for availability of good data and specific databases for purpose of risk assessment in road transportation is then highlighted and stressed. The complete procedure for accident investigation and data collection is developed and presented in the research and a conceptual model for a typical human centered reliability databases in road transportation is also developed. The research is novel and innovative and expected to pave the way for improvement and development of new risk mitigating systems and better assessment and monitoring of the safety of users on roads and with the capability of information sharing resulting in saving many lives worldwide.

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Chapter Nomenclature

Chapter 2:

λ : Distribution parameter as failure rate

t : Time

$R(t)$: Reliability at time t

$f(t)$: Density function

$F(t)$: Cumulative distribution function

b : Shape parameter of Weibull distribution

β : Scale parameter of Weibull distribution

$\lambda(t)$: Time dependent failure/error rate at time t

$\lambda_V(t)$: Failure rate of vehicle at time t

$\lambda_E(t)$: Failure rate of road environment at time t

$\lambda_F(t)$: Failure rate of human due to fatigue at time t

$\lambda_H(t)$: Failure rate of human due to non- fatigue factors at time t

$\lambda_{vi}(t)$: Failure rate of component i th of vehicle at time t

$\lambda_{ei}(t)$: Failure rate of component i th of road environment at time t

$\lambda_{fi}(t)$: Failure rate of component i th of human due to fatigue at time t

$\lambda_{hi}(t)$: Failure rate of component i th of human due to non-fatigue factors at time t

$P_i(t)$: Probability of the system being in state i at time t in Markov model

Chapter 3:

R_{system} : Reliability of system

Chapter Nomenclature

Chapter 3: (Continued)

$R_{Switch-A\ to\ B}$: Reliability of switching mechanism from system A to system B

$R_{Switch-B\ to\ C}$: Reliability of switching mechanism from system B to system C

$R_{Switch-C\ to\ D}$: Reliability of switching mechanism from system C to system D

$R_A(t)$: Reliability of driver operating the vehicle at time t (A)

$R_B(t)$: Reliability of ADAS warning system at time t (B)

$R_C(t)$: Reliability of ADAS crash avoidance system at time t (C)

$R_D(t)$: Reliability of vehicle passive system at time t (D)

$f_A(x_A)$: Probability density function of driver failure (A)

$f_B(x_B)$: Probability density function of ADAS warning system failure (B)

$f_C(x_C)$: Probability density function of ADAS crash avoidance system (C)

$x_{A\ or\ B\ or\ C\ or\ D}$: Time of failure of component A or B or C or D

Chapter 4:

$R_{IM}(t)$: Reliability of standby system composed of individual module of
driver, ADAS warning and ADAS crash avoidance components at time t

$R_{i,IM}(t)$: Reliability of standby system composed of individual module i of
driver, ADAS warning and ADAS crash avoidance components at time t

$R_{MPM}(t)$: Reliability of standby system composed of multi parallel modules
of driver, ADAS warning and ADAS crash avoidance components at time t

Chapter Nomenclature

Chapter 4: (Continued)

$R_{VUM}(t)$: Reliability of pedestrian crossing on roads for vehicle with Individual standby module at time t

$R_{VMM}(t)$: Reliability of pedestrian crossing on roads for vehicle with multi standby modules at time t

$F_{VUM}(t)$: Failure of pedestrian crossing on roads for vehicle with individual standby module at time t

$F_{VMM}(t)$: Failure of pedestrian crossing on roads for vehicle with multi standby modules at time t

$R_{A/B}$: Reliability of switching mechanism from system A to system B

$R_{B/C}$: Reliability of switching mechanism from system B to system C

$R_{Ai}(t)$: Reliability of component i of driver operating the vehicle at time t

$R_{Bjp}(t)$: Reliability of component jp of ADAS warning system at time t

$R_{Ckd}(t)$: Reliability of component kd of ADAS crash avoidance system at time t

$f_{Ai}(x_{Ai})$: Probability density function of failure of component i of Driver

$f_{Bjp}(x_{Bjp})$: Probability density function of failure of component jp of ADAS

Warning system

x_{Ai} : Time of failure of component i of driver

x_{Bjp} : Time of failure of component jp of ADAS warning system

λ_A : Pedestrian error/failure rate due to lack of awareness towards signals/crossing

Chapter Nomenclature

Chapter 4: (Continued)

λ_P : Pedestrian error/failure rate due to personal reasons (e.g., health, attitude, alcohol)

λ_D : Pedestrian error/failure rate due to poor human factors design of signals/crossing zone

λ_{SL} : Failure rate of crossing signals

λ_{SG} : Failure rate of crossing signage

λ_R : Failure rate of road surface of crossing area

λ_M : Failure rate of crossing markings

λ_V : Failure rate of crossing visibility

$P_0^{PB}(t)$: Probability of being in state 0 (safe mode) at time t due to effect of pedestrian behavior

$P_0^{IE}(t)$: Probability of being in state 0 (safe mode) at time t due to effect of road infrastructure and environment

$P_i(t)$: Probability of being in state i at time t in Markov model

Chapter 5:

IC_{DUI} : Cognitive impact factor of driving under influence

IP_{DUI} : Physical impact factor of driving under influence

IC_{DRT} : Cognitive impact factor of driving in risky traffic situations

Chapter Nomenclature

Chapter 5: (Continued)

IC_{AWS} : Cognitive impact factor of failure in ADAS warning systems

IP_{DRT} : Physical impact factor of driving in risky traffic situations

IC_{NMF} : Cognitive impact factor of not staying medically fit for driving

IP_{NMF} : Physical impact factor of not staying medically fit for driving

IC_{IAD} : Cognitive impact factor of inadequate awareness for driving by older drivers

IP_{IAD} : Physical impact factor of inadequate awareness for driving by older drivers

IC_{RIE} : Cognitive impact factor of failure in infrastructure & environmental conditions

IP_{RIE} : Physical impact factor of failure in infrastructure & environmental conditions

IC_{RAC} : Cognitive impact factor of failure in road based ADAS communication technologies

IP_{RAC} : Physical impact factor of failure in road based ADAS communication technologies

IC_{ODB} : Cognitive impact factor of other drivers' failure due to behavioral reasons

IP_{ODB} : Physical impact factor of other drivers' failure due to behavioral reasons

IC_{ODIE} : Cognitive impact factor of other drivers' failure due to infrastructure & environmental conditions

IP_{ODIE} : Physical impact factor of other drivers' failure due to infrastructure & environmental conditions

IP_{AWS} : Physical impact factor of failure in ADAS warning systems

IC_{OAWS} : Cognitive impact factor of failure in other vehicles' ADAS warning systems

Chapter Nomenclature

Chapter 5: (Continued)

IP_{OAWS} : Physical impact factor of failure in other vehicles' ADAS warning systems

$C_{DUI}(t)$: Cognitive load caused by driving under influence at time t

$C_{DRT}(t)$: Cognitive load caused by driving in risky situations at time t

$C_{NMF}(t)$: Cognitive load caused by not staying medically fit at time t

$C_{IAD}(t)$: Cognitive load caused by inadequate awareness for driving by older drivers
at time t

$C_{RIE}(t)$: Cognitive load caused by poor/failure in infrastructure & environmental
conditions at time t

$C_{RAC}(t)$: Cognitive load caused by failure in road based ADAS communication
technologies at time t

$C_{ODB}(t)$: Cognitive load caused by other drivers failure due to behavioral reasons at
time t

$C_{ODIE}(t)$: Cognitive load caused by other drivers failure due to infrastructure &
environmental conditions at time t

$C_{AWS}(t)$: Cognitive load caused by failure in ADAS warning systems at time t

$C_{OAWS}(t)$: Cognitive load caused by failure in other vehicles' ADAS warning system
at time t

$P_{DUI}(t)$: Physical load caused by driving under influence at time t

$P_{DRT}(t)$: Physical load caused by driving in risky situations at time t

$P_{NMF}(t)$: Physical load caused by not staying medically fit at time t

Chapter Nomenclature

Chapter 5: (Continued)

$P_{IAD}(t)$: Physical load caused by inadequate awareness for driving by older drivers at time t

$P_{RIE}(t)$: Physical load caused by failure in infrastructure & environmental conditions at time t

$P_{RAC}(t)$: Physical load caused by failure in road based ADAS communication technologies at time t

$P_{ODB}(t)$: Physical load caused by other drivers' failure due to behavior at time t

$P_{ODIE}(t)$: Physical load caused by other drivers' failure due to road infrastructure & environment at time t

$P_{AWS}(t)$: Physical load caused by failure in ADAS warning systems at time t

$P_{OAWS}(t)$: Physical load caused by failure in other vehicles' ADAS warning systems at time t

HC_{OAWS} : Human capacity of other drivers in relation to their vehicle's ADAS warning system

HC_{ODBIE} : Human capacity of other drivers in relation to their behavior, infrastructure & environment system

HC_{DB} : Human capacity of older drivers in relation to their behavior

HC_{IE} : Human capacity of older drivers in relation to road infrastructure & environment

Chapter Nomenclature

Chapter 5: (Continued)

HC_{AWS} : Human capacity of older drivers in relation to their vehicle's ADAS warning system

a, \dots, v : Any value in an identified scale (e.g., hypothetical scale of 0 to 50) to determine the upper limit of workload imposed by specific factors

Chapter 6:

$R(t)$: System reliability at time t

$F_{Y-T}(t)$: Failure probability of younger drivers causing crash at time t as total result of own failure and/or vehicle's ADAS, and design of safety systems

$F_{Y-T-F}(t)$: Failure probability of younger drivers as total result of own failure at time t

$F_{Y-B-F}(t)$: Failure probability of younger drivers as the result of own risky behavioral failure at time t

$F_{Y-RIE-F}(t)$: Failure probability of younger drivers as the result of road infrastructure & environment failure at time t

$F_{ADAS-T-F}(t)$: Failure probability of younger drivers as total result of ADAS failure at time t

$F_{ADAS-W-F}(t)$: Failure probability of younger drivers as the result of ADAS warning failure at time t

Chapter Nomenclature

Chapter 6: (Continued)

$F_{DV-T-F}(t)$: Failure probability of younger drivers as the total result of design of vehicle failure at time t

$F_{PS-F}(t)$: Failure probability of younger drivers as the result of passive safety system failure at time t

$F_{VP-F}(t)$: Failure probability of younger drivers as the result of preventive systems failure at time t

$F_{OV-T-F}(t)$: Failure probability of younger drivers as the total result of other vehicle's failure at time t

$F_{OD-F}(t)$: Failure probability of younger drivers as result of other drivers failure at time t

$F_{OADAS-F}(t)$: Failure probability of younger drivers as result of other vehicle's ADAS failure at time t

$F_{OADAS-W-F}(t)$: Failure probability of younger drivers as result of other vehicle's ADAS warning failure at time t

$F_{Y-IE-F}(t)$: Failure probability of younger drivers as result of own inexperience failure at time t

$\lambda_{Y-IE-RM}(t)$: Instantaneous failure rate of younger driver due to inadequate experience based awareness on rules and manouvering/steering skills at time t

Chapter Nomenclature

Chapter 6: (Continued)

$\lambda_{Y-IE-ASHR}(t)$: Instantaneous failure rate of younger driver due to inadequate experience based awareness & skills on hazards and risk recognition and control at time t

$\lambda_{Y-O-ADAS-CA}(t)$: Instantaneous failure rate of younger driver due to other vehicles' ADAS crash avoidance failure at time t

$\lambda_{Y-O-ADAS-WS}(t)$: Instantaneous failure rate of younger driver due to Failure in ADAS warning system of other vehicles at time t

$\lambda_{Y-O-ADAS-RWS}(t)$: Instantaneous failure rate of younger driver due to failure in reaction to ADAS warning by other drivers at time t

$\lambda_{Y-O-VB}(t)$: Instantaneous failure rate of younger driver due to other drivers' violations resulting from behavioral reasons at time t

$\lambda_{Y-O-RIE}(t)$: Instantaneous failure rate of younger driver due to other drivers' failure resulting from road infrastructure & environment at time t

$\lambda_{Y-O-LSVP}(t)$: Instantaneous failure rate of younger driver due to lack of special & highly visible plate on novice younger drivers' vehicle at time t

$\lambda_{Y-O-IE}(t)$: Instantaneous failure rate of younger driver due to lack of experience at time t

$\lambda_{Y-B-RVT}(t)$: Instantaneous failure rate of younger driver due to driving in risky manner violating traffic rules at time t

Chapter Nomenclature

Chapter 6: (Continued)

$\lambda_{Y-B-RTS}(t)$: Instantaneous failure rate of younger driver due to driving in risky traffic situations at time t

$\lambda_{Y-B-UI}(t)$: Instantaneous failure rate of younger driver due to driving under influence at time t

$\lambda_{Y-B-PS}(t)$: Instantaneous failure rate of younger driver due to driving with no parental supervision at time t

$\lambda_{Y-RIE-C}(t)$: Instantaneous failure rate of younger driver due to poor/failure in infrastructure & environmental conditions at time t

$\lambda_{Y-RIE-ADAS}(t)$: Instantaneous failure rate of younger driver due to failed road based ADAS communication technologies at time t

$\lambda_{Y-VADAS-CA}(t)$: Instantaneous failure rate of younger driver due to failure in ADAS crash avoidance systems at time t

$\lambda_{Y-VADAS-WS}(t)$: Instantaneous failure rate of younger driver due to failure in ADAS warning system at time t

$\lambda_{Y-VADAS-RWS}(t)$: Instantaneous failure rate of younger driver due to failure in reaction to ADAS warning system at time t

$\lambda_{Y-VD-PACC}(t)$: Instantaneous failure rate of younger driver due to unsafe design of critical components at time t

Chapter Nomenclature

Chapter 6: (Continued)

$\lambda_{Y-VD-PASS}(t)$: Instantaneous failure rate of younger driver due to failure in passive safety systems at time t

$\lambda_{Y-VD-PRAL}(t)$: Instantaneous failure rate of younger driver due to failure in alcohol detector engine lock at time t

$\lambda_{Y-VD-PRSL}(t)$: Instantaneous failure rate of younger driver due to failure in seatbelt wear lock engine system at time t

Chapter 7:

HRA : Human reliability analysis

HEP : Human error probability

PSF : Performance shaping factor

FTA : Fault tree analysis

$Z(t)$: Hazard or instantaneous failure rate

$R(t)$: Reliability at time t

$f(t)$: Probability density function

$F(t)$: Cumulative distribution function

$Z(t)$: Hazard or Instantaneous Failure Rate Function

$Z_c(t)$: Cumulative hazard function

λ : Constant failure rate

t : time

Chapter Nomenclature

Chapter 7: (Continued)

α : Mean time to failure

θ : Scale parameter

β : Shape parameter

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION

The human error is reported as a major root cause in road accidents in today's world and as the result a very large number of people lose their lives worldwide annually due to road accidents. The human although is the person in control of vehicle until the moment of crash but it has to be understood that the human is under continued impact by various factors including road environment, vehicle and human's state, abilities and conduct.

The current advances in design of vehicle and roads have been intended to provide drivers with extra comfort with less physical and mental efforts, whereas the fatigue imposed on driver is just being transformed from over-load fatigue to under-load fatigue and boredom. A representational model to illustrate the relationships between design and condition of vehicle and road as well as driver's condition and state on fatigue and the human error leading to accidents has been developed. Thereafter, the stochastic mathematical models were developed to make prediction on the road transportation reliability and failure probabilities due to each cause (vehicle, road environment, human due to fatigue, and human due to non fatigue factors). Furthermore, the supportive assessment methodology and models to assess and predict the failure rates of driver due to each category of causes were developed and proposed.

The human acting as a driver in road vehicles is constantly exposed to changing surroundings (e.g., road conditions, environment, and surrounding vehicle position) which

deteriorate his/her capacities leading to a potential accident. The auto industries and transportation authorities have realized that similar to other complex and safety sensitive transportation systems, the road vehicles need to rely on both advanced technologies (i.e., Advanced Driver Assistance Systems (ADAS)) and Passive Safety Systems (PSS) (e.g., seatbelts, airbags) in order to mitigate the risk of accidents and casualties. In this research, the advantages and disadvantages of ADAS as active safety systems as well as passive safety systems in road vehicles have been discussed. Also, this study proposes models that analyze the possible interactions between human as a driver and ADAS and PSS in the design of vehicles. Thereafter, the mathematical models have been developed to make reliability prediction at any given time on the road transportation. Finally, the implications of this study in the improvement of vehicle designs and prevention of casualties are discussed.

The research then integrated pedestrian as another vulnerable user on road transportation systems. A very large number of pedestrians die every year across the globe in both developed and developing countries. A pedestrian is under constant influence by various factors including the approaching vehicles equipped with Advanced Driver Assist Systems (ADAS), road infrastructures, environment and pedestrian's state, abilities and conduct. Author's view in the analysis of road accidents has been to identify and address the root causes of pedestrian-to-vehicle accidents. It is a simplistic approach to blame on human error as the cause of accidents whether on part of drivers or pedestrians and not to address the causes of human errors logically, systematically and dynamically. The interfaces and dependencies among identified causes of pedestrian-to-vehicle accident as unwanted event have been illustrated using fault tree in this research. Furthermore, the time dependent

reliability and failure probability functions of each of the contributing causes of this unwanted event have been modeled distinctively. Subsequently, the failure probability and reliability functions of pedestrian crossing on roads are determined. The results of this research will assist researchers and practitioners to logically and stochastically predict and analyze risk of the pedestrians involved accidents and provide measures in elimination or reduction of this risk.

Addressing the specific conditions and needs of older drivers on roads, the research then integrated this group of vulnerable drivers into the study. There has been a marked increase in the number of older drivers across the globe. The aging comes with limitations in physical, sensory and perceptual abilities affecting driving by the older people. The mobility is a universal fundamental right of living which cannot be taken away. However, the mobility of older people by their own vehicles demands special considerations by transportation authorities and the older drivers themselves. The number of crashes and severity of casualties caused by older drivers indicate that the older drivers should be considered as vulnerable users on roads and a risk to others. The research identified the potential causes of crashes by the older drivers and modeled the risk of crash using Fault Tree Analysis (FTA). As the human involved causes in the FTA are constantly under influence from each other, their effects impact proportionally and accumulatively on the total level of workload imposed on driver. This characteristic has been mathematically modeled and integrated into the developed FTA. The transportation authorities and auto industries can benefit from this research to further advance the design of technologies used in vehicles and roads and to better analyze and address the risk caused by older drivers on roads.

As another group of vulnerable users on roads, the research integrated the specific needs and characteristics of younger drivers into this study. There has been a marked increase in the number of young drivers across the globe. This age category comes with deficiencies resulting from their inexperience and age related characteristics. Mobility is a fundamental right of living by everyone whether young or old and learning to drive is considered as a significant achievement in youth's life. However, the mobility of a younger driver by his/her own vehicles demands special considerations. The number and types of crashes caused by younger drivers indicate that they shall be considered as vulnerable users on roads and a risk to others (i.e., other motorists, pedestrians and passengers). The research identified and illustrated the potential causes of crashes by younger drivers and introduced the available measures to mitigate the crash risk. The risk of crash by younger drivers was systematically and logically modeled using Fault Tree Analysis (FTA). Subsequently, the risk state of driving by younger driver at a given time was mathematically modeled. Furthermore, the concept of "riskometer" as an interactive in-vehicle tool to monitor the risk state of driving for younger drivers on road was proposed. The research concluded with discussions and recommendations on directions for potential applications and future research works.

For many years there has been increasing concern about the effects of human error in safety and reliability of complex systems like road transportation. Such accidents can in theory be predicted and prevented by risk assessment, in particular assessing the human contribution to risk. As part of the Human Reliability Assessment (HRA) process, it is usually necessary not only to define what human errors can occur, but how often they will occur, by assigning human error/failure probabilities (HEPs) to the identified human errors. These data in road transportation system can originate from various data sources such as

incident and accident reports, records, near-miss reports, violations, simulators, experts, automatic data recorder, human data recorder, and experiments. There are two major types of human error/failure data (i.e., qualitative and quantitative data) which can be collected. Lack of data is probably the single most important factor impeding the development of human reliability assessment and subsequently prediction of road accidents and taking proactive measures by the authorities. It is to acknowledge that there have been some efforts in many countries and sometimes regionally in developing the road transportation databanks. However, what it can be noticed from all these databanks is that their attentions are more leaning towards the consequence of road accidents on human than the recognition of causes of human error and the detailed characteristics and analysis of conditions leading to the error. The significance of the status and conditions of available human reliability databanks and necessity for development of HRA based database have been examined and highlighted in this research. Then, the required structure and framework for the future databanks in road transportation and the complete investigation methodology for crash data collection are proposed.

Lack of understanding of the failure distribution characteristics of drivers on roads at any given time is a factor impeding the development of human reliability assessment and prediction of road accidents in order to take best proactive measures. The author's proposed predictive behavioral characteristics of drivers in light of their instantaneous error rate was experimentally tested and validated in this research to further assist in processing and analysis of data collection as part of risk assessment. The findings of this research can assist transportation authorities to collect the necessary data, to better

understand the behavioral characteristics of drivers on roads, to make more accurate risk assessments, and finally to come up with the right preventive measures.

1.2 LITERATURE REVIEW

1.2.1 CAUSES OF DRIVER'S ERROR LEADING TO ROAD ACCIDENTS

The failures in transportation systems impact on the economy, environment and people's life [1.1]. Around 0.8 million fatalities and 20–30 million injuries occur each year in the globe as the result of road accidents [1.2, 1.3]. A large number of people lose their lives worldwide annually due to road transportation and accidents (e.g., 42000 loss of life annually in highway accidents alone in USA; 22000 loss of life annually due to road accidents in Iran as a developing country with almost one fifth of US population; 40000 road fatalities and 1.7 million injuries within the European Union (EU-15) each year) [1.4, 1.5, 1.6]. The road accidents are the second most serious cause of fatalities and injuries for EU citizens and for Europeans under 45 years of age the road accidents are the largest cause of death [1.7]. These data reflect the significance of problem and the fact that both developed and developing countries are in need of further research in reliability of road transportation systems.

Based on various studies on road accidents in both developed and developing countries, the human error or failure has been identified as the main cause of road accidents in 65% to 90% of cases [1.8, 1.9, 1.10, 1.11, 1.12]. The human error research has rooted in such safety critical domains as aviation, nuclear, and patient safety [1.13, 1.14, 1.15, 1.16], rather little research has systematically investigated the factors contributing to driver error or

failure [1.17]. This and any future research in this area are needed to constantly improve the reliability of road transportation systems.

In literature, the task load related fatigue is broken down into task over-load fatigue and task under-load fatigue [1.18, 1.19, 1.20, 1.21]. The former deals with the problems when the task requirements exceeding the ability of the concerned individual, and the latter is concerned with repetitive performance, lack of intellectual input, lack of proper opportunities to use individual's acquired skills or prolonged static tasks [1.18, 1.19, 1.20, 1.21].

With the ongoing advancement in automation level of vehicles, the task under-load fatigue is taking larger and different stake of drivers' general fatigue level compared to older days where the fatigue mostly was in the form of task over-load fatigue [1.21]. Besides human fatigue, there are three other main categories of accident causing factors in roads (i.e., road environment, vehicle, human due to non-fatigue factors) [1.21]. There is no doubt that the driver's fatigue state has significant impact on the human error and consequently on the safety and reliability of transportation systems [1.21]. Today, these factors are considered as contributing causes of human error or failure leading to road accidents.

Reliability engineering, which was originally developed to deal with the failures of the components, it is now understood that the reliability assessment of complex systems shall focus not only on hardware failure but also increasingly attributed on human error [1.22, 1.23].

The human error is seen as the most significant cause of accidents or incidents in any safety critical system [1.24]. Human error is defined as the failure to carry out a specified task that could result in disruption or damage to operations, equipment and safety

[1.25, 1.26]. In literature, the human error is divided into slips (attention failures), lapses (memory failures), mistakes (rule and knowledge based failures) and violations (any behavior deviated from accepted standards and rules) [1.27, 1.28, 1.29]. The human error is to be seen as the symptom of deeper trouble and it is not to be considered as the conclusion of investigation [1.30, 1.31]. This research intends to take some initiative steps in assisting road transportation authorities to deeply investigate and address the problem of human error or failure on roads.

The accident causing factors in roads can be grouped under the following categories [1.9, 1.21, 1.32, 1.33, 1.34]:

- Human related factors (e.g., speed, inattention, distraction, inexperience, reckless/irresponsible behavior, alcohol/drugs, emotional distress, fatigue)
- Road related factors (e.g., markings, street lighting, road maintenance, traffic, highway design, road signs, weather)
- Vehicle related factors (e.g., wheels, steering, braking, engine, lighting, seating, noise, vibration)

Human reliability is defined as the probability of successful completion of a task (e.g., driving operation) by an individual without degrading the system, and due to the significant role that human plays in the failures and risk of complex systems such as transportation system, the human reliability assessment (HRA) is seen critical [1.1, 1.35, 1.36]. The quantitative and qualitative assessment of human errors is named human reliability assessment (HRA), which deals with the difficult and complex area of how human error can impact on risk and how the human error potential can be reduced [1.37]. This research is

utilizing HRA approach in initiative way to model and address the problem of human error in road transportation systems.

The human reliability or error data required for the assessments can in general be obtained from such sources as incident or accident reports, violations, simulators, experts, data recorder, experiments, and probability compounding methods but a strong preference has been given to real data [1.9, 1.38, 1.39, 1.40]. Other than “Computerized Operator Reliability and Error Database” (CORE-DATA) containing Human Error Probability (HEP) data from nuclear power, process control, offshore, military, rail and air traffic domains along with their related background information [1.41, 1.42], there is no already available and widely applicable human error databases similar to the reliability databases of physical components (e.g., OREDA, RAC-PRISM/MIL-HDBK-217) [1.43, 1.44, 1.45]. Therefore, the author has highlighted the significance of need for reliability data in road transportation systems.

A typical HRA study includes such steps as representing the human contribution to risk of system (e.g., via fault tree, Markov model), quantification of the human error probabilities (HEPs) using databanks and real data, evaluating the risk, and then reduction of the human error contribution [1.46, 1.47]. This research has followed this general guideline of HRA to logically and systematically examine, model and improve the reliability of road transportation systems in initiative ways.

1.2.2 SAFETY AND VEHICLES EQUIPPED WITH ADVANCED DRIVER'S ASSISTANCE SYSTEM (ADAS) AND PASSIVE SAFETY SYSTEMS (PSS)

The daily road accidents result a huge cost to our modern life [1.48]. Organization for Economic Co-operation and Development (OECD) [1.49] reported that the road accident is considered as the primary cause of death for European males under age 45. Each year more than one million people die worldwide in traffic crashes and further fifty million people are seriously injured as the result of driving [1.50]. These data illustrate the seriousness of reliability problem in road transportation systems and the crucial need for research works in this domain.

Because the condition of road systems is constantly changing, drivers constantly have to make dynamic adjustments and adaptations to their driving behavior in response to the dynamic changes [1.51, 1.52]. There is no doubt that driver's error is a major factor in road fatalities [1.32, 1.53, 1.54, 1.55]. The driving performance is impaired when insufficient attention is devoted to the driving tasks [1.51, 1.56, 1.57]. Literature pertaining to the driver's distraction or inattention highlighted reduced longitudinal [1.58, 1.59] and lateral control [1.60, 1.61], reduced situation awareness [1.62], and degraded response times to road hazards as the results of distraction or inattention [1.63, 1.64]. The technology (e.g., CD player, GPS map, cell phones) and non technology based (e.g., sightseeing, talking with passengers) distractions [1.51] cause an increased risk of crash involvement [1.65]. It has been shown that both human (e.g., fatigue, distraction) and non-human related factors (e.g., weather, vehicle, road) could contribute to cause driver's error leading to an accident [1.21, 1.48, 1.53, 1.54, 1.66, 1.67, 1.68]. Therefore, the development of counter measures (e.g.,

Advanced Drivers Assistance System (ADAS) and Passive Safety Systems (PSS)) to mitigate the human errors becomes critical [1.49, 1.51, 1.69].

About 14,000 lane change and road departure crashes could have been prevented with warning systems in vehicles in the European Union [1.70]. Furthermore, Kuehn et al. [1.71] mentioned almost 24,000 rear-end, 2,000 lane change, and 3,000 road departure crashes could be prevented in Germany if the vehicles had crash avoidance technologies. The occupant survivability subsequent to crashes has been increased with improvements in vehicle design [1.72], and the recent approach in automobile designs is to avoid crashes altogether [1.73].

The reduction or elimination of road transportation casualties can be achieved by integrating both “Active” and “Passive” safety approach in design of vehicles [1.74]. The passive safety system refers to the safety technology embedded in a vehicle, which is specifically designed to reduce injuries in the event of a crash (e.g., airbags and advanced seat belt) [1.74]. On the other hand, the active safety refers to technologies that are designed to prevent crash incidence (e.g., Intelligent Speed Adaptation (ISA), Lane Departure Warnings (LDWs), Speed Warning) [1.74]. ADAS aims at supporting drivers by either providing the warning to reduce risk exposure (e.g., driving over the speed limit, raising driver alertness [1.75]) or triggering control tasks which takes over the vehicle control to eliminate many of the driver errors leading to accidents [1.76], to prevent DUI (Driving under Influence) [1.77, 1.78], and to assist in a better control of the vehicle (e.g., improving visibility of the road environment [1.75]). Now, technologies such as forward collision warning and avoidance systems, lane departure warning, side view assist, adaptive headlights, adaptive cruise control, and many more have become available in the market and

many more are under development [1.73, 1.76]. ADAS functions can be achieved through either an autonomous approach that includes on board intelligent vehicle systems, and roadside systems or cooperative approach which rely on interfaces between the vehicle and other vehicles on road and the road system components [1.73]. The use of ADAS system may have several positive impacts such as mitigation of exposure to risky conditions, and improvement of driver behavior (e.g., reduced driving speed and speed variability, smaller lane deviations, faster reaction times, less harsh braking and enhanced alertness) [1.75] and eradication of driver errors [1.17]. However, the potential negative effects include: 1) drivers' shifted attention to road environment information that causes insufficient attention to the primary driving tasks [1.75], 2) inappropriate driver reactions (e.g. harsh braking) that results in unexpected warnings [1.75], 3) driver frustration with warning systems due to unnecessary frequent system warnings, 4) driver frustration when certain elements of the driving tasks are taken over by the system in contrast to driver's desire [1.75]. The positive impact of PSS is to protect the lives of people in case of accident as the last resort by designers in the event of human and ADAS failures [1.75]. However, the ill designed (e.g., when the airbag is inflated late or seatbelt breaks under intense impact) and equipped PSS may result in injuries and even death for passengers and driver involved in accident [1.75].

The concept and functions of some of the available ADAS technologies are described as follows:

Cooperative Based Systems connect individual vehicle by communication to the other vehicles or road infrastructures [1.79]. With inter-vehicle communication, for example, forward collision warning and avoidance, systems can send an emergency braking message to its following vehicles [1.80] or a vehicle can send Global Positioning System

(GPS) data to the other vehicles in order to warn them of approaching vehicles beyond their range of view [1.81]. Also, road operators can provide drivers with dynamic information such as conditions of road surface, traffic, and weather [1.76]. Road train systems, which could connect the leading vehicle to the following vehicles let the driver experience hands and feet free of driving tasks while the computer system takes control [1.82].

Forward Collision Warning and Collision Avoidance Systems are developed to reduce rear-end collisions, which represent about 28% of all collisions between vehicles [1.83]. The system is made up of cameras and radar sensors to monitor the area in front of a vehicle [1.73]. Forward collision warning systems provide warnings (visual, audible, haptic) to a driver when the occurrence of imminent crash with the leading vehicle is likely [1.84] and the collision avoidance systems take action only if the driver fails to respond to the warning presented, for example by applying a limited or full brake [1.76].

Side and Rear View Assistant Systems use cameras or radar sensors to monitor surrounding areas of a vehicle and warn the driver of vehicles in the side or rear blind zones [1.57, 1.73].

Lane Departure Warning Systems use cameras to monitor vehicle position within the lane, warning the driver if the vehicle is in risk of straying across lane markings [1.73, 1.85, 1.86, 1.87].

Vision Enhancement Systems capture and present the road scene with a greater contrast in situations with degraded visibility using an infrared camera with either head-up or head-down display (HUD/HDD) [1.17, 1.88].

Adaptive Cruise Control Systems is used for a longitudinal vehicle control with the use of a microwave radar, sensor, and distance control device by maintaining a safe gap

such that the set speed of the vehicle is maintained until the leading vehicle gets slower speed than the following vehicle. This results in reduction of the speed in the following vehicle [1.17, 1.89].

Vigilance Monitoring System monitors time that driver's views are off the road and it warns the driver if his/her eyes are off the road for an extended time [1.90] as head position and eye closure are strong indicators of fatigue [1.91]. Thiffault and Bergeron [1.92] found that the visual monotony is a key input to driver fatigue.

Navigation System assists a driver in planning routes and navigates in real time so that the driver may be advised of when to join or leave roads safely in a timely manner [1.17].

As described above, the human error though can be reduced by addressing the causes of driver's error but we should know that it can never be eliminated. Therefore, the need for ADAS to monitor and correct driver's state in relation to roads is seen vital. Since warning and corrective functions of ADAS may also fail and driver error does occur, thus as the last resort all vehicles are equipped with PSS to reduce the severity of accident consequences. This research has therefore integrated the interactions between driver and ADAS and PSS in order to have a realistic assessment of the reliability of today's road transportation systems.

1.2.3 SAFETY OF PEDESTRIANS ON ROADS

It is projected that the road casualties, due to growth in global population and subsequently a denser traffic will rise by about 65% over the next 20 years unless there is an increased commitment to prevention [1.93, 1.94, 1.95].

The continuing efforts have been made domestically and internationally to improve the protection of vulnerable road users against injuries and fatalities, in particular for pedestrians, however, the situation of pedestrian safety is still critical and worrisome [1.96]. China has been consistently ranked as a country with high percentage of pedestrian fatality rates [1.96], such that in 2006 more than 89,455 persons died in 378,781 accident cases, among which, pedestrians accounted for 26.01%, the highest proportion of all traffic fatalities [1.97]. In China, on average, every 5 minute a pedestrian is injured and one is killed every 17 min [1.97]. Furthermore, in USA as a country with developed road infrastructure and system, pedestrian safety is still worrisome such that there were 4,432 pedestrian fatalities and an estimated 69,000 injuries in traffic crashes in year 2011 [1.98, 1.99]. On average, a pedestrian died every two hours and injured every eight minutes in US traffic crashes [1.99]. Same report cites that in 2011 the pedestrian deaths in US accounted for 14.9 percent of all traffic fatalities, and made up 4.5 percent of all the people injured in traffic crashes. Furthermore, in a developing country like Iran with almost one fifth of US population, it has been reported that 2,374 pedestrians were killed in traffic crashes in year 2011, which accounted for 21.2 percent of road traffic fatalities [1.6]. These data from both developed and developing countries highlight the importance of research in pedestrian safety domain.

Traffic is the result of interaction between people, vehicles and road infrastructure in which the human is a key element and nearly all traffic accidents are due to human error [1.100, 1.24]. Based on various studies on road accidents in both developed and developing countries, the human error committed by drivers, which may endanger the safety

of pedestrians as well, has been identified as the main cause of accidents in 65% to 90% of cases [1.8, 1.9, 1.10, 1.11, 1.12].

The road system is constantly changing and as the result drivers must continuously make dynamic driving behavior in response to these changes in the road environment [1.51] and as the result safety of pedestrians is under constant threat by drivers. With respect to pedestrian errors as other potential cause of pedestrian-vehicle accidents, according to a study pedestrian errors have been found as the cause of accidents in 59% of the vehicle to pedestrian crashes in North America [1.101]. Pedestrians may either disregard traffic signals or cross roads facilities as a typical kind of pedestrian error [1.102] or make error unintentionally due to failure in crossroad infrastructures and environment. However, whether the errors committed by pedestrians are caused negligently or intentionally, they can lead to traffic accidents [1.103, 1.104, 1.105]. The traffic accident statistics signifies the importance of understanding factors causing pedestrian errors [1.102] and subsequently to eliminate or reduce the risk. The measures to counteract traffic accidents involving pedestrians and vehicles can be grouped under one of three approaches: (1) change pedestrians' behavior; (2) provision of vehicle related measures; and (3) physical road infrastructure related measures [1.100]. Each of these three groups of counter measures shall contain both passive and active safety systems; the former aim to mitigate the consequences of an accident once it has happened and the latter aim to avoid accidents [1.100].

Pedestrian's error can be considered as a kind of results of bad crossing behavior [1.100]. Therefore, the analysis of pedestrian crossing behavior has been of great concern to researchers [1.106]. Pedestrian crossing behavior is expected to be impacted by various factors, such as personal characteristics, traffic and road infrastructures and environmental

factor [1.102]. Pedestrians' personal (e.g., age, gender, attitudes, health) characteristics play an important role in pedestrian safety crossing [1.107, 1.108, 1.109, 1.110, 1.111, 1.112]. Furthermore, a recent study revealed that pedestrians in poor neighborhoods are injured on roads 6 times more often than in rich neighborhoods due to difference in pedestrians' behavior, busier traffic and denser population [1.113]. Changing behavior is expected to be promoted and performed by enforcement, information, education, as well as driving instruction; it is to be noted that this matter is falling mainly in the domain of active safety [1.100].

Hojjati-Emami et al. [1.21] illustrated how drivers are constantly influenced by various human, environmental, vehicular and overload/under-load fatigue factors forcing them to commit error leading to an accident. The goal of elimination and reduction of the causes of drivers' error therefore requires multi facet measures by all players including auto industries, transportation authorities, law enforcement, drivers, etc. However, it is to be noted that the goal of elimination of these contributing factors to drivers' error can never be completely achieved but the errors can effectively be reduced. For example, human under-load fatigue as a new form of fatigue causing accidents perhaps can never be eliminated. Thus, today's transportation system is resorting more and more on providing technologies to detect the human errors and to mitigate them. However, it is to be noted that these technologies cannot take over all drivers' role and they are not 100 percent reliable either. Subsequently, the modern vehicles are typically equipped with both passive and active safety systems so that if the active safety systems fail to act effectively then a level of protection as passive safety system is activated as last resort in accidents through passive safety systems [1.74, 1.114]. As an example of specifically designed passive safety system

for pedestrians, we can mention the pedestrian safety airbag which is an inflatable cushion along the rear edge of the hood to prevent pedestrian's head from hitting the windshield when struck by the car [1.115]. However, all or majority of the ADAS technologies, as active safety systems, directly or indirectly affect the safety of pedestrians as well as driver and passengers. Though, there are some specifically designed ADAS for pedestrians. One of them is the recently developed pedestrian detection system, which stops the vehicle when it recognizes someone entering the roadway [1.115]. Another one is the new driver aid that can spot pedestrians and cyclists before drivers can detect in congested traffic or poor weather using Wi-Fi technology and pedestrians' cellular phones together with the sensors and other driver aids built into vehicle [1.116].

It is well-know that the road infrastructures (e.g., signals, markings, road structure, signs) and environment (e.g., fog, ice rain, snow) have impact on performance of both pedestrians and drivers. Consequently, it is expected that the safety of pedestrians may be endangered by both their own error and drivers. The road infrastructure related measures mainly concentrate on active safety (i.e., roads constructed in a way that accidents are less likely to occur) but also to some extent on passive elements (i.e., consequences of accidents are less severe) [1.100]. The concept of "Self-explaining roads" as one of the active measures indicates on a recognizable road layout which promotes appropriate behavior by both drivers and pedestrians [1.117]. Self-explaining roads present road users with a clear road structure where they should be and what they should do to maintain safety [1.117]. For example, pedestrians' designated area indicates on where to cross and to caution drivers to lower their speed and restrict overtaking [1.117, 1.118]. The "Forgiving roads" is another approach in design of roads which aims to protect road users in the event of a crash through

reduction or elimination of the consequences of accidents once they occur with provision of structural layout elements (e.g., safety fences or landscape are used to separate fast moving traffic from pedestrians and to cushion crashes when they happen) [1.117, 1.118]. Besides the elements of road construction which is built into physical layout of roads, the safe roads infrastructure shall possess the static and dynamic information displays and devices (e.g., signage, markings, displays, lights) [1.117, 1.118]. Therefore, if the road is not designed based on physical and cognitive abilities of human either as driver or pedestrian and has not taken into account the environment of the road location in its design, there would be a higher expected rate of vehicle to pedestrian accidents.

The information provided above has helped the author to model the reliability of systems composed of pedestrian and vehicle in order to propose effective tools for assessment of such system and mitigating the risks.

1.2.4 OLDER DRIVERS ON ROADS

The number of older people has increased over the course of last decades and is expected to be continued in all parts of the globe mainly due to better health care system [1.119, 1.120, 1.121]. For example, in 2012 the population of people over 65 years in Canada, USA, China and Iran has reached 16.4%, 13.5%, 9.1% and 5.1% of their total population, respectively and are expected to increase to 24.9%, 19.6%, 17.2% and 8.9% by year 2030; respectively [1.121]. These data reflect the significant and growing proportion of older population in the societies specifically in developed world.

People over 65 years are expected to have one or more chronic conditions causing relevant disabilities (e.g., arthritis, hearing impairment, heart disease, orthopedic

conditions, disorientation, limited attention, memory impairment, decreased ability for learning, declined vision, lower muscle strength, degraded selective and divided attention, and lower speed of information processing) [1.119, 1.122, 1.123, 1.124, 1.125, 1.126]. A disability may be a combination of physical, cognitive, sensory and emotional causing impairments and activity limitations [1.127]. However, all people with disability have the same human rights as other members of society and should be empowered to exercise their rights [1.128].

One of the fundamental rights is Mobility, as the ability to get wherever one needs to go, which is accounted essential for everyday functioning and a satisfactory life [1.129, 1.130]. To better enjoy a high quality of life, older adults shall be able to access needed goods and services and to participate in desired social and leisure activities independently and the automobile is accounted as the primary means of transportation [1.129]. The automobile is used by almost 85% of the elderly as drivers and 60% as passengers [1.131, 1.32]. Many elders cannot use public transportation due to their functional limitations and poor quality of services [1.133, 1.134].

Older drivers constitute the fastest growing segment of the driving population [1.135, 1.136, 1.137]. For example, the number of licensed older drivers (65+) in Canada and USA has reached more than 14.5% and 15.7% of their total Drivers population; respectively, reflecting the increasing trend from previous years [1.138, 1.139].

The driver's license serves as a symbol of independence, self-sufficiency and, for the older person; it may also serve as symbol of functional competence [1.136, 1.140, 1.141]. Driving cessation is associated with a dramatic decrease in participation in activities outside the home and depression [1.142]. Rather than stop driving completely, older adults

often engage in self-regulatory behaviors through avoiding high-risk situations (e.g., dense traffic, complicated intersections, adverse weather, and night driving) [1.135, 1.136].

It is widely recognized that older driver safety and mobility may be compromised due to age-related changes [1, 143, 1.144]. The accident rate is about six times higher for the 75 years old and older than for the average of all ages [1.145]. Additionally alarming is the fact that increased age is associated with a higher risk of being seriously injured or killed in an automobile crash [1.136, 1.145]. On average, 10 older drivers (over 65 years) are killed and 500 injured every day in crashes in USA [1.146]. Furthermore, the older Drivers (over 65 years) fatalities accounted for 16.9% of total crash fatalities in Canada larger than their share of 14.5% in total drivers' population [1.147].

Driving involves a complex interaction between sensory, cognitive and motor processes [1.137]. Physical, sensory, and cognitive abilities of people decline during the normative aging process affecting the performance of everyday tasks including driving [1.147, 1.148]. In addition, the elderly are more likely to have multiple medical conditions and take multiple medications, whose interactions may further affect safe driving performance [1.147, 1.149]. The age at which the declines start as well as the rate at which these declines continue differ from person to person [1.150]. Also not every weakness of the older drivers has negative consequences on road safety [1.119, 1.150]. Furthermore, despite the age related weaknesses affecting the safe driving, as more significant ones are highlighted below, there are some strengths (e.g., experience, conservative risk behavior) among older drivers on which can partially be relied.

It is evident that good vision is very important for safe driving. However, it has been noted that such visual functions as peripheral vision, motion perception, visual acuity,

darkness adaptation, contrast sensitivity, and color vision decline as people age [1.122, 1.123, 1.124]. Hearing is perhaps not as critical as sense of vision in driving, but it is still important component of safe driving (e.g., hearing the warnings given by surrounding vehicles). The prevalence of hearing problems increases with advanced age [1.151]. As drivers age, they become less able to hear the higher frequencies sounds in normal intensity level and it becomes more difficult for the older driver to filter out unwanted noises [1.152]. Age related cognitive changes produce a general slowing in the ability to perceive and process information and to act upon. Specifically, these declines are noted in their vigilance, selective and divided attention, short-term memory, information-processing speed, and reaction/response times [1.152, 1.153, 1.154]. Perceptual and cognitive processes are needed to select the appropriate information, interpret it, and make decisions which must then be translated into an appropriate driving action. Physical abilities, that decline as people get older, are reduced joint flexibility, reduced muscular strength, and reduced manual dexterity influencing the ability to get in and out of a car and to operate the vehicle, which have impact on injury and recovery [1.124].

Nevertheless, it is to be noted that older drivers will be less prone to risky traffic situations unlike young drivers (e.g., driving less often under the influence of alcohol and complying more often with traffic rules) [1.143, 1.146, 1.155, 1.156]. Furthermore, they usually have a great deal of driving experience enabling them to anticipate the situations they would encounter gaining extra time to think and act, thereby partly compensating their aged abilities [1.119].

The information described above signify the fact that a special care and attention should be given to older drivers safety as vulnerable users on roads.

Considering the identified causes of high accidents rate among older drivers, a set of measures aiming to reduce the road casualties involving older adults have been explored and utilized in many parts of world (e.g., provision of education/information for older adults, infrastructural adaptations, and in-vehicle technologies) [1.152, 1.157].

A recent focus of vehicle design with respect to safety has been in the development of new technologies (e.g., advanced drivers assistance system) aimed at enhancing the capabilities and supporting the weaknesses of the older driver and therefore to extend the safe driving life of older adults [1.75, 1.76, 1.119]. The advanced driver assistance systems (ADAS) can mainly provide assistance for older drivers specifically with respect to their limitations in motion perception, peripheral vision, selective and divided attention, decreased speed of processing information, visual motor capabilities, and decision making (e.g., [1.158, 1.159, 1.160, 1.119, 1.161, 1.162]. The limitations of older drivers while designing ADAS have to be addressed well as they are more susceptible to the consequences of poorly designed ADAS than younger drivers [1.163]. Some of the currently available ADAS assisting the older drivers include visual enhancement systems, vigilance monitoring device, park assistance system, basic and advanced collision warning and avoidance systems, adaptive cruise control, adaptive headlights, electronic stability control, lane departure warning, and emergency response system [1.114, 1.65, 1.121, 1.125, 1.164, 1.165, 1.166, 1.167, 1.168, 1.169]. It is to be noted that in-vehicle technologies designed specifically for the older drivers have the potential to improve safety and mobility for all motorists [1.137, 1.75]. However, the number of initiatives to develop ADAS that are aimed at the special safety needs of older drivers is yet limited [1.162].

The design of roadways may also help to compensate age-associated difficulties with driving tasks [1.170, 1.171]. Roadways that communicate with in-vehicle technologies (e.g., navigation and route guidance system) can provide older drivers with helpful information on the traffic and road conditions and best route to take and ultimately affect positively the safe driving [1.75, 1.125, 1.166, 1.172]. The technology of communicating from vehicle to roads and environment (e.g., automatic collision notification and vehicle location sensors in vehicles) have also the capability of automatically transmitting vehicle location and position to the nearest 911 center and emergency medical services (EMS) once the air bags are deployed [1.125, 1.168, 1.173]. Furthermore, the roadways can directly communicate with users through such technology as Talking Signs system composed of permanent audio signals transmitters installed on public locations (e.g., traffic lights and government buildings) and the receivers carrying by visually impaired drivers, to assist them in getting the information related to surrounding environment (e.g., go/do not go and street information) [1.172, 1.174, 175].

Another focus of vehicle design with respect to safety has been in the development of mandated installation of passive safety equipment, such as safety belts and air bags enhancing the capabilities of the vehicle in the event of crash [1.65, 1.158]. Furthermore, the suitable design of automobile components (e.g., seating, mirrors, headlight, sun visors, interior noise level, pedals) can contribute effectively in increased visibility and subsequently would facilitate early detection of possible roadway problems by older drivers, considering that they require more time to process information and respond [1.65, 1.176].

Assistive Technology is a generic term for devices that help a person to overcome or remove a disability in order to accomplish tasks (e.g., hearing aid, eye glasses,

wheelchair, large print, and Talking Signs System) [1.172, 1.175, 1.177]. Mann [1.178] has listed some of the typical problems with assistive devices (e.g., difficulty to use, not sufficiently assist person to do intended task, and unsuitability for every environment/situation). Since it is expected that older drivers due to their limitations to use some of these devices while driving, therefore it is required to know and predict their impact on safety of driving.

For the safety of older drivers, and that of others, the older drivers need to pay special attention to their limitations as they get older [1.173]. The older adults shall use smart risk strategies (e.g., how/when/where to drive considering their limitations, getting re-trained for driving, not driving under influence of alcohol/medications/fatigue/distractions, and medically checked) to reduce the likelihood of motor vehicle-related crashes [1.173, 1.179].

The described limitations of older drivers and the already available risk mitigating technologies been integrated into this research to specifically assess and monitor the reliability of such road transportation systems.

1.2.5 YOUNGER DRIVERS ON ROADS

Youth period is the time in which youths experience growth, experimentation, powerful emotions while exploring their limits and pushing these boundaries [1.180]. This period also coincides with the time when most people learn to drive for first time [1.180]. Unfortunately, this combination results in a high traffic safety risk for young drivers, their passengers, and other road users (i.e., motorists, pedestrians [1.180, 1.181]).

Nevertheless, one of the fundamental rights for everyone's satisfactory life is mobility [1.129, 1.133, 1.134] and many youths resort to driving their own vehicle despite the risk and costs.

The number of youths has constantly being decreased over the course of last decades due to lower fertility rate and this pace is expected to continue in all parts of the globe [1.182]. For example, in 2013 the population of people between 15-24 in Canada, USA, China, and Iran has now reached 12.9%, 13.7%, 15.4% and 19.8% of their total population, respectively [1.182]. The ratios are expected to decrease to 11.0%, 13.0%, 11.1% and 14.1% by year 2030, respectively [1.182].

However, younger drivers constitute the second fastest growing segment of the driving population just behind older drivers in most parts of the world [1.138, 1.139]. For example, the number of licensed youth drivers (15-24) in Canada and USA has reached more than 12.79% and 13.05% of their total drivers population; respectively [1.138, 1.139].

The driver's license serves as a symbol of independence, maturity, competence and self-sufficiency for an individual while learning to drive is one of the most achievements for everyone [1.140, 1.141, 1.180, 1.183].

Younger people aged 15-24 represent only 13% of the U.S. population, however, they account for 30% (\$19 billion) of the total costs of motor vehicle injuries (i.e., medical treatment, property damage and other costs) among males and 28% (\$17 billion) of the total costs of motor vehicle injuries among females [1.184, 1.185]. The percentage of drivers' fatalities and serious injuries in Canada among age category of 15-24 were reported 22.3% and 23.6%; respectively [1.147]. These data reflect that the younger drivers are under extremely high risk of fatalities and serious injuries on roads compared to any other age

groups in Canada and elsewhere (e.g., 37 members of OECD) when comparing the data with their proportion in total population (e.g., 12.9% in Canada) or in total number of licensed drivers (e.g., 12.79% in Canada) [1.182, 1.186].

The motor vehicle crashes still considered as the leading cause of deaths among youths (16-20) and young adults (21-24) in USA [1.187], whereas for the first time since 1981, motor vehicle traffic crashes were not among the top 10 causes of death in the United States for population as a whole [1.187, 1.188]. A long-standing challenge for road safety research is that young novice drivers, aged 25 years or younger, have disproportionately high crash involvement [1.180, 1.189, 1.190].

To reduce the risk, young novice drivers shall engage in self-regulatory behaviors through avoiding high-risk situations (e.g., dense traffic, complicated intersections, adverse weather and night driving) and obeying the law while not taking risky driving behavior [1.135, 1.36]. Furthermore, the transportation authorities as well as auto companies need to address this issue through multi facet measures such as design of safer and smarter automobiles, training, enforcement, graduated driver's licensing, supervision, and monitoring [1.191].

Driving involves a complex and constant interaction between cognitive and motor processes of a driver [1.137, 1.183]. Driving demands both procedural and higher-order cognitive skills [1.192]. Handling or procedural skills involve executing a sequence of actions, which may become automated with extensive practice such as vehicle manoeuvring or manipulation of vehicle controls [1.193]. Higher-order cognitive skills involve situation monitoring, assessment, response planning and execution [1.194].

Research indicates that novices have a less holistic perception of road stimuli and traffic hazards than experienced drivers [1.195] and detect hazards less quickly and efficiently [1.196]. Novice younger drivers develop handling or procedural skills quickly and efficiently and they often perceive these improvements as evidence that they are highly skilled drivers [1.181]. However, this confidence in handling skills is not supported by the complex perceptual and cognitive skills required for detecting hazard and risk perception since they have limited experience of the traffic environment [1.181, 1.197]. Younger drivers are more likely than older or middle age drivers to underestimate dangerous situations and not be able to recognize hazardous situations [1.197, 1.198, 1.199]. Besides, the younger drivers are still expected to be less skilled in terms of procedural or handling skills than more experienced drivers.

The elevated crash risk among younger drivers is due largely to inexperience, but are exacerbated by age related developmental factors (i.e., peer influence, poor perception of risk, over confidence, aggression, and high emotionality) as the result of emotional, cognitive and neurological development of youths [1.197, 1.200, 1.201, 1.202, 1.203, 1.204].

The following are some of available statistics to support the above stated claims:

- 15 percent of teen drivers who were involved in fatal crashes were distracted at the time of the crash [1.185, 1.197, 1.205],

- 37 percent of male drivers aged 15-20 who were involved in fatal crashes were speeding at the time [1.185, 1.206],

- the motor vehicle death rate for male drivers and passengers aged 16 to 19 was almost two times that of their female counterparts [1.188, 1.197, 1.207],

-teenage drivers and passengers are among those least likely to wear the seat belts [1.164, 1.185, 1.189],

-among male drivers between 15 and 20 years of age who were involved in fatal crashes, 25% had been drinking despite the fact that the risk of alcohol consumption for younger drivers while driving is much greater than others [1.208, 1.209].

Considering the high accident rate among younger drivers, a set of measures as listed below have been explored and utilized in many parts of world aiming to reduce the road casualties involving younger drivers [1.189, 1.210].

Most traditional driver education programs (i.e., pre-license and post-license) provide classroom training on the rules and skills required on the road and a few hours of behind the wheel training [1.211]. Pre-license training programs aim to develop the skills that are required to obtain a driver's license and drive safely, such as basic vehicle control and traffic assessment [1.192]. Post-license training programs aim to enhance skills that are considered relevant to crash prevention including skid control, hazard recognition and advanced vehicle control skills [1.192].

Many authorities now use graduated driver licensing systems (GDLSs) in which younger drivers first gain supervised driving experience on a learner's permit, then progress to unsupervised but restricted driving on a provisional or probationary license, and finally attain a full unrestricted license [1.191, 1.192, 1.212, 1.213]. Research suggests that the most comprehensive graduated drivers licensing (GDL) programs are associated with reductions of 38% and 40% in fatal and injury crashes, respectively, among younger drivers [1.191, 1.214]. Graduated driver licensing policies when supported well by police enforcement

serve to limit exposure to the high risk conditions, allowing young drivers to gain experience only under less risky driving conditions [1.191, 1.215, 1.216, 1.217, 1.218].

A growing body of research indicates that close parental management of younger drivers can lead to less risky driving behavior, fewer traffic tickets, and fewer crashes [1.215, 1.219]. Supervision by parents at home can further enhance the driving awareness of their child and considered as a very good source for transfer of knowledge and experience. When child is on road, parents can act as a co-pilot or ADAS who constantly monitors the operation and warn the driver, once it is perceived necessary, to ensure nothing fails.

Besides risk taking behavior of younger drivers (e.g., speeding, distractions) resulting from their age related developmental characteristics, there are other pervasive problems with young drivers due to their inexperience (e.g., failure to recognize and manage roadway hazards) [1.210, 1.220, 1.221]. A recent focus of vehicle design has been in the development of new technologies (ADAS) aimed at enhancing the capabilities and supporting the weaknesses of the younger drivers and therefore to extend the safe driving life of younger drivers [1.75, 1.76, 1.210, 1.221].

The advanced driver assistance systems (ADAS) can mainly provide assistance for younger drivers specifically with respect to the following [1.220]:

- Managing distractions to keep the driver focused on the road in hazardous situations,
- Monitoring the driver to avoid driving while he/she is fatigued, drunk or distracted,
- Warning and intervention in collision situations,
- Providing route guidance to relieve drivers of the burden of route finding,
- Providing immediate and aggregate feedback regarding driving performance,
- Identifying potential hazards, and

- Providing an environment that mitigates peer influence

Some of the currently available ADAS assisting the younger drivers include intelligent speed adaptation system (ISA), visual enhancement systems, vigilance/fatigue monitoring device, park assistance system, basic and advanced collision warning and avoidance systems, adaptive cruise control, electronic stability control, blind spot detector, seat belt reminder, alcohol interlock, black-box/journey data recording system, smart card, lane departure warning [1.114, 1.166, 1.69, 1.220, 1.121, 1.222, 1.223, 1.224, 1.225, 1.226, 1.227].

It is to be noted that in-vehicle technologies designed specifically for the younger drivers have the potential to improve safety and mobility for all motorists though these specific initiatives are yet limited [1.75, 1.137, 1.220, 1.224, 1.225, 1.228, 1.229].

The design of roadways may also help to compensate age-associated concerns with driving tasks [1.180]. Roadways that communicate with in-vehicle technologies (e.g., navigation and route guidance system) can provide younger drivers with helpful information on the traffic and road conditions and best route to take and subsequently affect positively the safe driving [1.75, 1.166, 1.230, 1.231]. The technology of communicating from vehicle to roads and environment (e.g., automatic collision notification, vehicle location sensors in vehicles) have also the capability of automatically transmitting driver's performance and vehicle location and position into the black box or nearest police station or emergency medical services (EMS) if needed [1.226, 1.230, 1.231].

The appropriate design of automobile components (e.g., advanced seatbelt reminder system, seatbelt engine interlock system, speed limiter, restricted electrical devices in vehicles, alcohol interlock engine system, front and side airbags, visible novice license

plate) are aimed to compensate the risky behavior characteristics and inexperience of young drivers and protect them as effectively as possible [1.221, 1.225, 1.232, 1.233].

Driving is a complex task and for the safety of younger drivers, and that of others, the younger drivers need to pay special attention to their limitations and characteristics [1.183]. The younger drivers shall use such smart risk strategies as how/when/where to drive taking into considering their limitations in order to reduce the likelihood of motor vehicle-related crashes [1.183, 1.225].

Self-awareness and self-monitoring are among various overlapping higher order cognitive skills which are forms of strategic processing or executive control [1.183]. They need be effectively incorporated in pre and post training and awareness sessions for younger drivers and be used in any risk mitigating measures. They include self-feedback, self-coaching, self-regulation, self-efficacy, self-reflection, self-learning, self-evaluation, self-reliance, self-control, self-direction, self-pacing, and self-motivation [1.183, 1.234, 1.235].

The growing population of younger drivers specifically in developed world and their special age related characteristics signify the need for research in the reliability of younger drivers on roads as vulnerable users on roads and as a matter of fact a risk to others.

1.2.6 HUMAN CENTERED RELIABILITY DATABASES FOR ROAD TRANSPORTATION

Around 0.8 million fatalities and 20–30 million injuries occur each year in the globe as the result of road accidents [1.2, 1.3]. It is projected that the road casualties, due to growth in global population and subsequently a denser traffic will rise by about 65% over the next 20 years unless there is an increased commitment to prevention [1.93].

It has been estimated in various research that human error is the primary cause of 60 to 90 percent of major accidents in complex systems such as nuclear power, process control, aviation, and sea, rail and road based transportation systems (e.g., [1.8, 1.9, 1.10, 1.11, 1.12, 1.21, 1.114, 1.169, 1.227, 1.236, 1.237, 1.238]).

Human Reliability Assessment (HRA) aims to assess and reduce human error potential in a system [1.239]. However, human-error data collection, which should arguably underpin the whole approach to HRA, has generally been an unfruitful area [1.37]. HRA has three basic functions including the identification of human errors, prediction of probability or likelihood of human errors (HEPs) and the reduction of their likelihood if required [1.240]. The ideal sources of human error (HE) data for these HRAs are empirical studies on human performance and accidents but there is limited availability of such data [1.46].

This has led to reliance on assessments by experts solely and/or with use of probability compounding methods which are based on expert judgment and original data from fields and experiments, and this procedure has been used in various areas [1.241]. However, several problems are associated with expert judgment and compounding methods (e.g., HEART, THERP) for HRA including inconsistencies of judgments and the difficulty in systematically considering performance shaping factors (PSFs), which are factors that influence human performance [1.40, 1.239].

The recognition that human errors affect competitiveness, customer satisfaction, safety and incurring costs to society has persuaded auto companies and the transportation authorities across the globe to dedicate programs to the systematic reduction of human errors [1.29, 1.242]. Concurrent with the increase in size and complexity on road transportation systems, there has been an increased risk associated with drivers on roads [1.37].

Understanding the events leading up to a motor vehicle crash is crucial in preventing the crash from occurring in the first place [1.208].

One of the most difficult aspects of addressing human performance reliability is obtaining good data including human error data [1.29, 1.242]. Failure data whether for human or physical components are the backbone of any reliability and risk studies [1.243]. There are two major types of human reliability data (i.e., qualitative and quantitative data) which need to be collected [1.44]. They can in general originate from various data sources such as incident and accident reports, near-miss reports, violations, simulators, experts, automatic data recorder, human data recorder, experiments and prediction models [1.244].

The backbone of a failure data system is the failure data collection form. A failure reporting and documentation system could be very effective if a careful consideration is given during its design [1.245]. Furthermore, such forms must be designed so that they require minimum effort to collect failure data and provide maximum benefits. Nonetheless, such data collection forms in general are designed to include information such as location and condition, failure description, damages, operating hours from previous failure [1.246]:

The experience in data collection has shown that the availability of road crash data often diminishes with the passage of time [1.208]. Most importantly, with the passage of time a driver's memory of events may fade and willingness to cooperate with the researcher may diminish, too [1.208]. This shall be achieved through prompt and multi-faceted investigations, interviews with the drivers, assessment of the vehicle components, and an evaluation of the roadway condition and geometry [1.208].

One of the most difficult aspects of addressing human performance reliability is obtaining the data. The existing data fall into two categories: human factors data and human

error data [1.29]. For the most part, the human factors data are in the form of design guidelines that are not reliability-explicit [1.29]. Williams [1.38] suggests that “many of the organizations operating in the reliability world already have partial human reliability databases of the sort necessary.

The following are some of the specific and more general human reliability databases:

DATASTORE is the first human reliability database developed by the American Institute for Research (AIR) containing time and human performance reliability estimates for human-engineering design features [1.247]. This database contains very fine scale data containing the motions of the human body, which is not generally applicable for studies in road HRA studies.

The NUCLARR (Nuclear Computerized Library for Assessing Reactor Reliability) is an automated database management system used to process, store, and retrieve human and equipment reliability data for nuclear power plants [1.248]. It is directly applicable to probabilistic risk analysis (PRA) and human reliability analysis (HRA), which is part of the PRA. The US Department of Energy Idaho National Engineering Laboratory manages NUCLARR and consistently updates and maintains the data [1.29]. The data tend to be plant and equipment specific with limited applicability outside the nuclear power industry [1.29]. The data in this database are nuclear based and therefore it has no applications in reliability assessment of drivers in road transportation.

CORE-DATA as a database of HEP data and associated background information was created in the 1990s to aggregate all usable existing data with new data into one single database [1.42]. The aim of COREDATA has been to collect HEP data and to support those

probabilities with associated background information. This has entailed creating a taxonomic structure, gathering existing data from nuclear power and process control domains, and collecting new data via studies over the past decade in offshore, military, rail and air traffic domains [1.40]. CORE-DATA contains taxonomies of industry, error, performance shaping factors, tasks, etc., to classify any data received or developed for inclusion in its database. The data come from non-road transportation sectors and are based on human error probabilities of questionable accuracy because the definition of the number of opportunities for errors is hard to determine.

There is no doubt that everyday some rich data are being collected, maintained and analyzed individually by various organizations (e.g., law enforcement, transportation ministries and councils, health care and emergency services, auto manufacturers, repair shops) throughout the world [1.249, 1.250, 1.251]. The road crash data are collected and stored electronically by Police and Transportation Authorities in many developed countries across the Globe (e.g., [1.252]). These data at best include the following information that does not meet all of the needs for a thorough human reliability assessment [1.250]. These data appear to be more applicable for insurance, law enforcement, health care, and economics effects on society purposes than for the systematic decision making needed for the elimination or reduction of the risks of accidents [1.251].

- Crash location,
- Road environment,
- Vehicles involved,
- Vehicles drivers,
- Vehicles passengers,

- People injured or killed in the crash and the circumstances including notes and a diagram indicating the movements of the vehicles involved,
- Factors that contributed to the crash (e.g., driving too fast for the conditions or failing to stop at a stop sign), and
- Integrative statistics on casualties, monthly accident indicators, etc.

As described above, there has been no systematic program across the world to identify, collect and share errors committed by road users, causes, mitigating strategies and follow up actions, and their contributing role in accidents and incidents [1.30]. This research intends to effectively highlight and address this issue in road transportation systems.

1.2.7 DISTRIBUTION CHARACTERISTICS OF DRIVERS'

INSTANTANEOUS FAILURE RATE

One of the very critical data necessary for human reliability assessment (HRA) in road transportation systems is the time to failure (i.e., from moment zero of the trip to time of accident) for each failure mode. This data is obtained to determine the distribution of instantaneous failure rate and subsequently to obtain such information as mean time between/to failure and reliability of the system [1.169, 1.238, 1.253, 1.254, 1.255]. This research stresses on the significance of this data and develops procedures and framework necessary to collect and utilize this data. In order to get a better picture of how human failure rate is occurring at any given time, the Hazard Plotting Method can be used. This method is a powerful graphical approach to perform failure data analysis [1.243, 1.256, 1.257]. The important advantage of the approach is that it indicates if the given data set

whether complete or incomplete belongs to the tried distribution and if so, then it estimates the associated parameters [1.243, 1.256, 1.257].

1.3 MOTIVATION AND OBJECTIVE OF THESIS

1.3.1 SHORTCOMINGS IN IDENTIFICATION AND INTEGRATION OF THE CAUSES OF DRIVERS' ERROR FOR SAFETY/RELIABILITY ASSESSMENTS OF ROAD TRANSPORTATION SYSTEMS

There is no systematic program across the world to contribute in the identification and understanding of driver errors and causes, and their role in accidents and incidents [1.30].

Unlike aviation and nuclear industries, the collected data in road accidents are not modeled and analyzed systematically and stochastically for the purpose of identification and assessment of root causes of driver error (e.g., [1.74]).

There has not also been any research as of today to model the relationships between causes of driver error including vehicle, road and driver's condition and state on fatigue and non-fatigue factors. Furthermore, there is no research in making prediction at any given time on the reliability and failure probability of road transportation systems.

1.3.2 SHORTCOMINGS IN SAFETY/RELIABILITY ASSESSMENTS OF DRIVING WITH VEHICLES EQUIPPED WITH ADAS AND PSS

The modern vehicles are typically equipped with both passive and active safety devices such that if the active safety measures fail to act effectively then a level of protection of the occupants is provided in accidents through passive safety systems [1.74].

There has been no study by now to propose models that analyze the possible interactions between human as a driver and ADAS and PSS in the design of vehicles and to be able to make reliability prediction at any given time on the road transportation. This paves the way for better assessment and improvement of the available safety measures to make roads safer.

1.3.3 SHORTCOMINGS IN SAFETY/RELIABILITY ASSESSMENTS OF PEDESTRIAN CROSSING ON THE ROADS

Our view in the analysis of road accidents has been to identify and address the root causes of pedestrian-to-vehicle accidents. It is a simplistic approach to blame on human error as the cause of accidents whether on part of drivers or pedestrians and not to address the causes of human errors logically, systematically and dynamically. There has been no study as of today to examine the root causes of vehicle to pedestrian accidents and their interfaces and dependencies systematically and stochastically and to determine the time dependent reliability and failure probability functions of each of those contributing causes. This paves the way for new technologies and mitigation measures to make roads safer.

1.3.4 SHORTCOMINGS IN SAFETY/RELIABILITY ASSESSMENTS OF OLDER DRIVERS ON ROADS

Driving is a complex task and can be affected by the changes that accompany aging. There has been no research yet to identify systematically and logically the potential causes of crashes by the older drivers and to model the risk of crash logically and stochastically. Furthermore, there has been no research to model the interactions of human involved causes

and their accumulative effects on the total level of workload imposed on driver paving the way for new technologies to monitor the state of driver and mitigate the error.

1.3.5 SHORTCOMINGS IN SAFETY/RELIABILITY ASSESSMENTS OF YOUNGER DRIVERS ON ROADS

The youth period comes with deficiencies resulting from their inexperience and age related characteristics. There has been no research to identify and illustrate the potential root causes of crashes by younger drivers and to model systematically and logically the risk of crash by younger drivers at any given time. Subsequently, the concept and details of “RISKOMETER” as an interactive in-vehicle tool to monitor the risk state of driving for younger drivers on road to make roads safer has been thought and presented for the first time in this research.

1.3.6 SHORTCOMINGS IN HUMAN RELIABILITY DATABASES FOR ROAD TRANSPORTATION SYSTEMS

Lack of appropriate data is perhaps the most important obstacle in development of human reliability assessment and subsequently prediction of road accidents and taking proactive measures by the authorities. All available databanks and data collection are leaning their attentions towards the consequence of road accidents on humans than the recognition of root causes of human error. This research is unique and it has provided a complete investigation and human failure data collection methodology and later proposed a model for the human centered reliability databanks for road transportation based on the needed structure and framework. The findings of research would pave the way for a novel systematic approach in

investigation of accidents and better analysis, monitoring, and sharing the data in the proposed database.

1.3.7 SHORTCOMINGS IN UNDERSTANDING THE CHARACTERISTICS OF DRIVERS' INSTANTANEOUS FAILURE RATE

The knowledge on failure distribution characteristics of drivers on roads is a factor assisting the development of human reliability assessment and subsequently making prediction of road accidents and taking best error mitigating measures. This research is unique in terms of experimentally testing and validating the proposed predictive behavioral characteristics of drivers in light of their instantaneous error rate over the course of driving period. The results would pave the way in better understanding of the driver's expected failure characteristics and allow researchers to model the prediction functions of drivers' reliability on the road and consequently to design the appropriate risk preventive measures.

1.3.8 OBJECTIVES

The major objective of this thesis is to identify the root causes of driver failures or errors in road transportation systems and to examine the available risk mitigating measures and then to systematically and mathematically model the causes with their interdependencies in order to develop the risk assessment and prediction models. The developed models and methodologies are aimed to assist authorities in better and more accurately assessing and monitoring the state of risks by road users at any given time. Furthermore, the proposed concepts and tools are intended to be used for designing new risk mitigating technologies on roads and in vehicles. The research also aims at addressing the problem of road accidents

investigation procedure and data collection, and processing and storage as a database for sole purpose of enhancement of the safety on roads.

1.4 THESIS STRUCTURE

The dissertation is divided into eight Chapters and a reference section listing references in six different subsections.

Chapter 1: This Chapter presents an overall and detailed view of significance and issues pertaining to reliability of road transportation systems based on a thorough literature review.

Chapter 2: This Chapter identifies the root causes of road accidents and illustrates the interactions of the causes leading to human error. The chapter also presents a model to evaluate the risk state of drivers on roads at any given time along with supportive models to determine the failure probability of each and every contributing cause of accidents.

Chapter 3: This Chapter presents the analytical approaches to model systematically and logically the interactions between human as driver with a vehicle equipped with ADAS Warning, ADAS Crash Avoidance Systems and PSS. The chapter also presents a model to evaluate the risk state of drivers at any given time.

Chapter 4: This Chapter presents the analytical approaches to identify the root causes of pedestrians-vehicles involved accidents and to model the risk state of pedestrians on roads for assessment of risk at any given time.

Chapter 5: This Chapter presents the analytical approaches to identify the root causes of older drivers involved accidents and to model the risk state of older drivers on road for assessment of risk at any given time. The chapter also presents a risk condition monitoring concept for older drivers built on the developed constrained FTA capturing the accumulative effects of causes.

Chapter 6: This Chapter presents the analytical approaches to identify the root causes of younger drivers involved accidents and to model the risk state of older drivers on roads for assessment of risk at any given time. The chapter also presents the concept of “RISKOMETER” for development of a new in-vehicle technology for condition monitoring of younger drivers’ risk.

Chapter 7: This Chapter presents a new and complete road accident investigation and data collection procedure with a detailed model for a human centered reliability database for road transportation. Furthermore, it examines the behavioral characteristics of drivers over the time in light of failure rate and experimentally test and validate the failure distribution characteristics of drivers on roads.

Chapter 8: This Chapter presents conclusions and future directions.

CHAPTER 2

THE INTEGRATIVE TIME-DEPENDENT MODELING OF THE RELIABILITY AND FAILURE OF THE CAUSES OF DRIVERS' ERROR LEADING TO ROAD ACCIDENTS

2.1 BACKGROUND

The likelihood of life threatening accidents as the result of direct failure in physical components of vehicle and roads are becoming dimmer day by day due to tougher competitions and stricter regulations.

Nevertheless, there are still some challenging issues in prevention of deadly accidents as the result of failure in the designed conditions of safe roads and vehicle components under severe environmental conditions. Furthermore, the human as driver may endanger the safety of transportation system due to both fatigue and non-fatigue factors such as behavior, poor skill, ill health, inexperience, etc.

This research incorporates the failure rates for all vehicle, environment, human fatigue and human non-fatigue factors into the developed stochastic models to make predictions on the reliability and failure rates of road transportation systems at any given time. Thereafter, some additional models and methodology were developed and proposed to be used for analysis, assessment, and prediction of the expected failure rates of road accidents due to each category of causes.

It is believed that this research is unique in its content and the way it investigates, discusses and addresses the problem of road transportation accidents mathematically and

descriptively in an integrative manner by taking into account both latent and active causes of road accidents.

2.2 CAUSAL REPRESENTATIONAL MODEL AND INSTANTANEOUS OCCURRENCE PATTERNS OF DRIVERS' ERROR

The fatigue nowadays is to be considered as a root cause of many of the road accidents. The relationship of fatigue with accidents as the result of human error is complex and increasingly becoming more significant, which demands a special attention. The fatigue not only may affect and get affected by the potential human accident causing elements (e.g., conduct, experience/skill) but also it is affected by the other two categories of accident causes (i.e., road environment and vehicle factors) as illustrated in Fig. 2.1 [2.1].

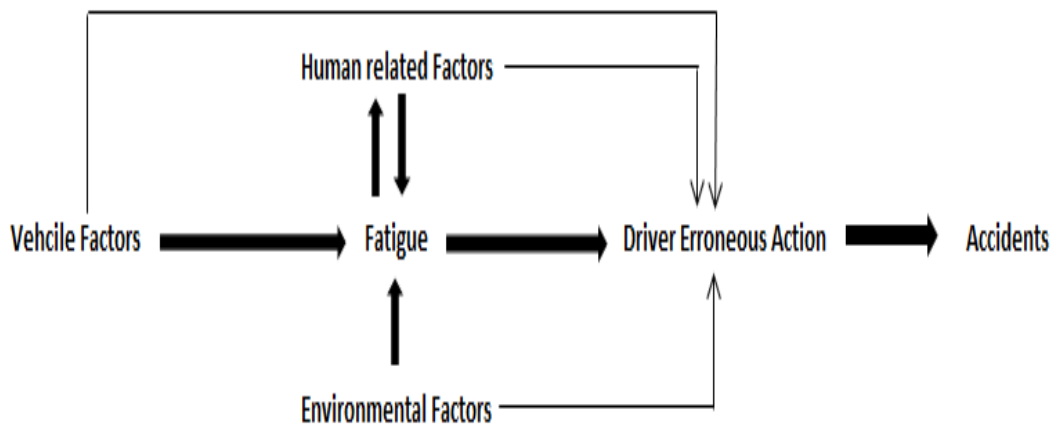


Figure 2.1-Cause and Effect Diagram of Road Transportation Accidents

The fatigue is defined as a state of being tired resulting from an excessive mental and/or physical work or boredom as a result of low mental/physical load, this state would result in reduction or an impairment of physical or mental human performance [2.2, 2.3].

The two aspects of fatigue, that is, mental and physical, interact upon each other so closely that to evaluate them separately is not possible [2.2]. The driving operation like many other tasks with modern innovations and technologies has been transforming more and more from physical work to mental work [2.2]. The effects of fatigue may consist of poor judgment, omission of results, in difference to essentials [2.4], reduced performance in activities requiring muscular force [2.5], decreased productivity, higher errors, and degraded quality [2.2, 2.6, 2.7].

According to a recent review [2.8] in literature, it was cited that there has been no study as yet to discuss or analyze the shapes that a fatigue accumulation function may take, thus those researchers assumed, for simplicity of their analyses that fatigue accumulates linearly. However, my review in literature came across with a reference [2.9] claiming that the fatigue increases exponentially with time. So, the author believes that it should be a fair and valid assumption for the simplicity of the reliability analyses to assume that fatigue accumulates exponentially.

As the result it is expected that the human reliability to decrease exponentially over the time meaning that the human error rate remains constant up to exhaustion point (Fig. 2.2) (as per Equations (2.1)-(2.3) [2.10, 2.11]).

$$f(t) = \lambda e^{-\lambda t} \tag{2.1}$$

$$R(t) = 1 - F(t) = e^{-\lambda t} \tag{2.2}$$

$$\lambda(t) = \frac{f(t)}{R(t)} = \lambda \tag{2.3}$$

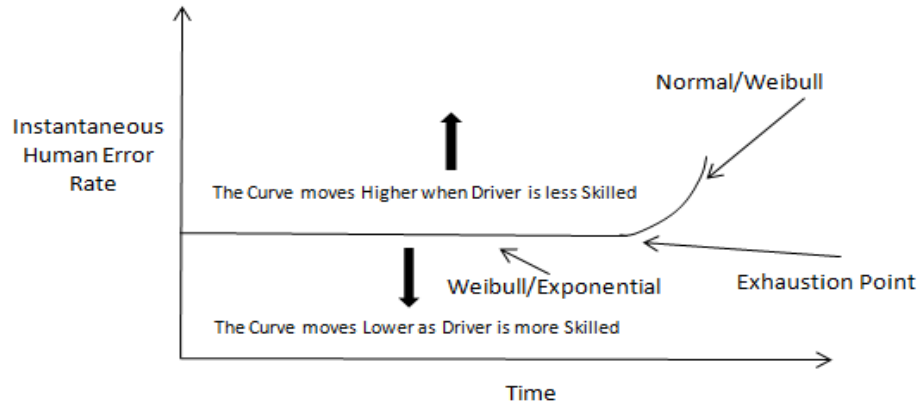


Figure 2.2 – Expected Characteristic of Human Error Rate in Driving Operation

Furthermore, it is to be noted that many drivers are tempted and inclined to pass the level of exhaustion in order to reach their destinations at desired time. Thus, the author has made another assumption on the shape of fatigue accumulation beyond the exhaustion point considering that the research in this area to the best of author's knowledge is missing. The human reliability is expected to deteriorate more drastically over the time beyond the exhaustion point (e.g., Weibull distribution with parameter b of greater than 1 similar to wear-out period of bathtub (Dhillon) curve as per Equations (2.4) and (2.5) [2.10, 2.11]).

$$F(t) = 1 - e^{-\frac{t^b}{\beta}} \quad (2.4)$$

$$R(t) = 1 - F(t) = e^{-\frac{t^b}{\beta}} \quad (2.5)$$

Consequently the instantaneous error rate would be expected to increase over the time drastically (Fig. 2.2) as per Equation (2.6) [2.10, 2.11].

$$\lambda(t) = \frac{bt^{b-1}}{\beta} \quad (2.6)$$

It is to be noted that Figure 2.2 does not contain the first part of a typical bathtub curve as shown in Fig. 2.3 typically used for the physical components [2.1]. Figure 2.3 is referring to the instantaneous human error rate in relation to time from the moment that driver sits on the car to make a trip [2.1]. Thus, there should not be any tangible difference in terms of instantaneous failure rate between time zero of the trip till the time driver gets to his/her exhaustion point [2.1]. The effects of driver's skill and experience can just make the curve, composed of two sections (i.e., constant line and the increasing curve), to move upper or lower as it is reflected in Fig. 2.2 [2.1]. That means the instantaneous human error rate for a novice driver is expected to be higher and for skilled person lower. So, no burning period like for physical components as shown in Fig. 2.3 exists for human error rate in a single trip [2.1]. Nevertheless, it has to be acknowledged that this does not mean that the burning period of bathtub curve does not apply in total driving life of a driver, that is, from the day he/she gets his/her driver's license till the day he/she reaches the level of maturity in terms of driving skill and experience [2.1].

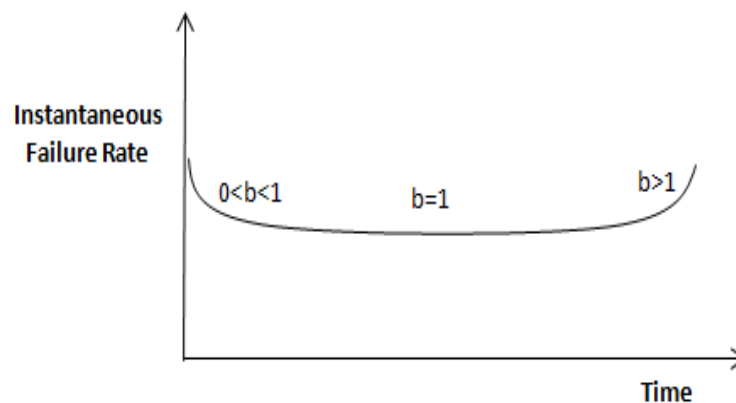


Figure 2.3-Bathtub (Dhillon) Curve

The bathtub (Dhillon) curve (Fig. 2.3) is used to show the characteristics of mechanical components containing three weibully distributed periods (i.e., burning period with a decreasing failure rate, useful life period with a constant failure rate, and wear out period with increasing failure rate attribute) [2.11]. The Weibull distribution tends toward an exponential distribution subject to $b=1$, toward normal distribution when $b>2$, and toward Ralyleigh distribution when $b=2$ [2.10].

2.3 THE STOCHASTIC PREDICTION MODEL FOR RELIABILITY OF TRANSPORTATION SYSTEMS

To the best of author's knowledge based on review in literature, there has been no research to develop the reliability modeling of road transportation systems through integration of both latent and active causes of road accidents (i.e., vehicle, road environment, human failure due to non-fatigue factors, and human failure due to fatigue) and to take into account the possibility of variation in instantaneous failure rate of vehicle, environment and human as opposed to constant failure rate over the life cycle of system [2.1].

The assumption of constant failure/error rate (i.e., exponential distribution) could not be considered realistic throughout the life cycle of system due to the expected changing failure rate of components for vehicle and roads during burning and wear out periods (Fig. 2.1) and the changing human failure/error rate beyond exhaustion level at any given time (Fig. 2.3) [2.1].

The author's view in the analysis of road accidents is to identify and address the root causes of accidents rather than simply blaming the human error as the cause of accidents [2.1]. This requires having a systematic understanding on the causation chain of

accidents similar to what it was presented in Figure 2.1 [2.1]. It is acknowledgeable that the operator/driver of transportation systems is the person in varying degree of control of vehicles up to the moment of accident depending on situation and severity of impacting factors [2.1]. However, on the other hand it is to be understood that there are four groups of constantly changing causes over the time to force or lead the human, as driver who is just an element of system, to make an accident causing error [2.1]. Based on this approach, Figure 2.1 can be converted into following stochastic mathematical modeling, Equations (2.7)-(2.11), for use in prevention, investigation, and reduction of accidents [2.1]. The Markov representation of states of safe and unsafe road transportation is illustrated in Figure 2.4 [2.1].

$$\frac{dP_0(t)}{dt} + (\lambda_V + \lambda_E + \lambda_F + \lambda_H)P_0(t) = 0 \quad (2.7)$$

$$\frac{dP_1(t)}{dt} - (\lambda_V)P_0(t) = 0 \quad (2.8)$$

$$\frac{dP_2(t)}{dt} - (\lambda_E)P_0(t) = 0 \quad (2.9)$$

$$\frac{dP_3(t)}{dt} - (\lambda_F)P_0(t) = 0 \quad (2.10)$$

$$\frac{dP_4(t)}{dt} - (\lambda_H)P_0(t) = 0 \quad (2.11)$$

It is to be noted that at time $t=0$, $P_0(t) = 1$, $P_1(t) = 0$, $P_2(t) = 0$, $P_3(t) = 0$, and $P_4(t)=0$.

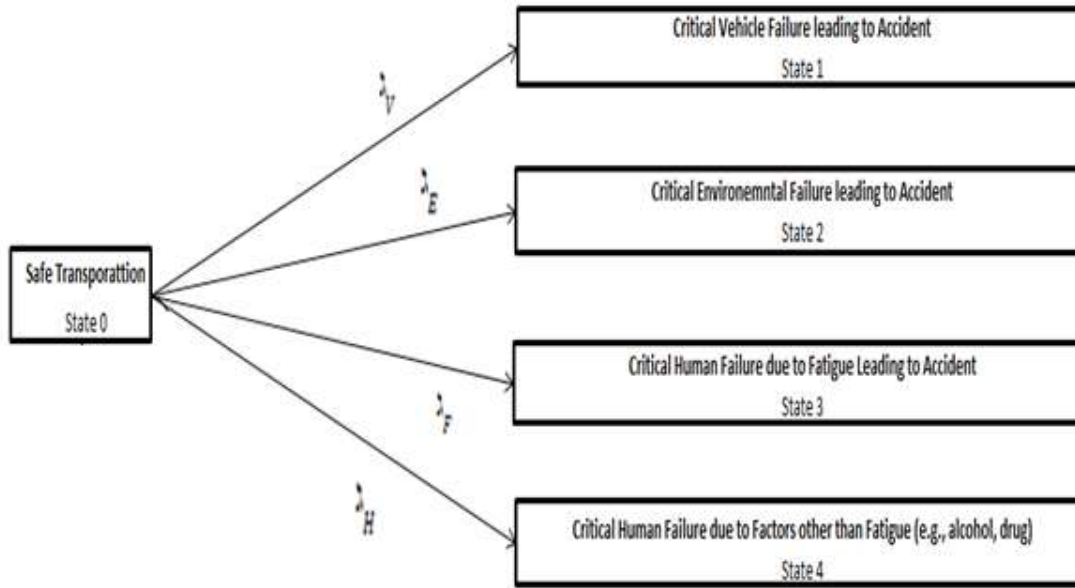


Figure 2.4-The Markov Model for Accidents in Transportation System

By taking Laplace of the above equations, solving them to obtain the equations for $P_0(s), P_1(s), P_2(s), P_3(s),$ and $P_4(s)$, and taking inverse Laplace from the derived equations, the reliability function (Equation (2.7)) and unreliability or failure probability functions of transportation system caused by vehicle, road environment, fatigue, and non-fatigue human factors (Equations (2.8)-(2.11)) at any given time t can be obtained from Equations (2.12)-(2.16) as follows [2.1].

$$P_0(t) = e^{-(\lambda_V + \lambda_E + \lambda_F + \lambda_H)t} \quad (2.12)$$

$$P_1(t) = \frac{\lambda_V}{(\lambda_V + \lambda_E + \lambda_F + \lambda_H)} (1 - e^{-(\lambda_V + \lambda_E + \lambda_F + \lambda_H)t}) \quad (2.13)$$

$$P_2(t) = \frac{\lambda_E}{(\lambda_V + \lambda_E + \lambda_F + \lambda_H)} (1 - e^{-(\lambda_V + \lambda_E + \lambda_F + \lambda_H)t}) \quad (2.14)$$

$$P_3(t) = \frac{\lambda_F}{(\lambda_V + \lambda_E + \lambda_F + \lambda_H)} (1 - e^{-(\lambda_V + \lambda_E + \lambda_F + \lambda_H)t}) \quad (2.15)$$

$$P_4(t) = \frac{\lambda_H}{(\lambda_V + \lambda_E + \lambda_F + \lambda_H)} (1 - e^{-(\lambda_V + \lambda_E + \lambda_F + \lambda_H)t}) \quad (2.16)$$

It is to be noted that the instantaneous failure rates of vehicle, road environment, human due to fatigue, human due to non-fatigue factors may be subject to variations over the time though in the above-presented Markov model for simplicity of calculation just their constant portions are used. With respect to failure rate of vehicle, λ_V , it is expected to follow a bathtub pattern as illustrated in Figure 2.3 (decreasing in infant-mortality period, constant in useful life period and increasing in wear-out period) [2.1]. Furthermore, the failure rate of human (driver) due to fatigue, λ_F , is expected to follow a pattern as shown in Figure 2.2, that is, its value stays constant up to exhaustion point and then increases over time [2.1]. However, the patterns or shapes of instantaneous failure rates and its prediction methodology for road environment as well as human due to non-fatigue factors are yet to be investigated and discussed in details by researchers, although these topics are just touched in Sections 2.5 and 2.6 [2.1].

As each of the stated causes for accidents (i.e., vehicle, road, human fatigue, and non-fatigue human factors) consists of different sub-components, therefore their reliability values could safely and reasonably be estimated based on the common practice of industries that the reliability of a system composed of many components is obtained with just taking the assumption that the components are all in series structure [2.1, 2.12, 2.13, 2.14].

Thus, the reliability of each of vehicle, road environment, human due to fatigue, and human due to non-fatigue factors can be estimated, using Equation (2.17) [2.10], by Equations (2.18)-(2.21) [2.1].

$$R(t) = e^{-\int_0^t \lambda(t) dt} \quad (2.17)$$

$$R_V(t) = \prod_{i=1}^n e^{-\int_0^t \lambda_{vi}(t) dt} \quad (2.18)$$

$$R_E(t) = \prod_{i=1}^n e^{-\int_0^t \lambda_{ei}(t) dt} \quad (2.19)$$

$$R_F(t) = \prod_{i=1}^n e^{-\int_0^t \lambda_{fi}(t) dt} \quad (2.20)$$

$$R_H(t) = \prod_{i=1}^n e^{-\int_0^t \lambda_{hi}(t) dt} \quad (2.21)$$

Consequently, the instantaneous failure rates for each of accident causing factors can be obtained from Equations (2.22)-(2.25) [2.1, 2.10, 2.11].

$$\lambda_V(t) = -\frac{1}{R_V} \times \frac{dR_V(t)}{dt} \quad (2.22)$$

$$\lambda_E(t) = -\frac{1}{R_E} \times \frac{dR_E(t)}{dt} \quad (2.23)$$

$$\lambda_F(t) = -\frac{1}{R_F} \times \frac{dR_F(t)}{dt} \quad (2.24)$$

$$\lambda_H(t) = -\frac{1}{R_H} \times \frac{dR_H(t)}{dt} \quad (2.25)$$

It is to be noted that the values of $\lambda_V(t), \lambda_E(t), \lambda_H(t), \lambda_F(t)$, when all the constituting components of each of the causes (i.e., vehicle, road, fatigue and non-fatigue factors) are in their useful life periods (i.e., constant failure rates), can simply be obtained by $\sum_{i=1}^n \lambda_{vi}$,

$\sum_{i=1}^n \lambda_{ei}$, $\sum_{i=1}^n \lambda_{hi}$ and $\sum_{i=1}^n \lambda_{fi}$; respectively. Due to the complex nature of human failure due to fatigue, road environment failure and the human failure due to non-fatigue factors separate sections are allocated hereinafter to these subjects [2.1].

2.4 PREDICTION ASSESSMENT METHODOLOGY OF DRIVERS' FAILURE RATE DUE TO FATIGUE

The components of human failure due to fatigue perhaps are not separable and measurable as easy as other accident causing factors in particular vehicle and physical components of road environment [2.1]. One approach in identifying the components of human fatigue is to break it down to physical and mental components. That means to identify separately the failure rates of mental and physical components of human due to fatigue. As the failure in one of these components would suffice to fail the human in driving operation, therefore the series nature of the two components becomes evident [2.1]. Thus, the reliability and failure rate of human as driver due to fatigue can be obtained from Equations (2.20) and (2.24) [2.1].

It is to be noted that the values of $\lambda_{fi=1}$ (*physical component*), $\lambda_{fi=2}$ (*mental component*) are going to be in direct but weighted (W) relationships with physical and mental loads caused by vehicle condition ($VC_{physical\ load}$, $VC_{mental\ load}$), road environment ($RE_{physical\ load}$, $RE_{mental\ load}$), human's state of health, circadian state, abilities, skills, experience, and conduct ($HU_{physical}$, HU_{mental}), as well as the physical and mental boredom/under-load/static fatigue caused by vehicle ($BV_{physical}$, BV_{mental}), road environment ($BR_{physical}$, BR_{mental}), and human's state, interests, etc. ($BH_{physical}$, BH_{mental}) [2.1]. Thus, it can be proposed that

the following functions can be applied mathematically to analyze and predict the effects of various factors in failure rates of human due to physical and mental fatigue [2.1].

$$\lambda_{fi=1} \text{ (physical component)} \approx BV_{physical} \cdot (VC_{physical\ load} \cdot W_{VC-physical}) \times BR_{physical} \cdot (RE_{physical\ load} \cdot W_{RE-physical}) \times BH_{physical} \cdot (HU_{physical} \cdot W_{HU-physical}) \quad (2.26)$$

$$\lambda_{fi=2} \text{ (mental component)} \approx BV_{mental} \cdot (VC_{mental\ load} \cdot W_{VC-mental}) \times BR_{mental} \cdot (RE_{mental\ load} \cdot W_{RE-mental}) \times BH_{mental} \cdot (HU_{mental} \cdot W_{HU-mental}) \quad (2.27)$$

The poorer road, vehicle conditions, and human's state and interest in terms of posing excess of physical and mental fatigue (i.e., higher values for $VC_{physical}$, VC_{mental} , $RE_{physical}$, RE_{mental} , $HU_{physical}$, HU_{mental}), the higher the failure rates for human due to physical and mental fatigue can be expected [2.1]. Furthermore, it is important to note that the values of BV , BR and BH are expected to proportionally go up as the values of $VC_{physical}$, VC_{mental} , $RE_{physical}$, RE_{mental} , $HU_{physical}$, HU_{mental} reach and go pass the extreme range of lower values (i.e., extremely high degree of automation) [2.1]. Otherwise, they are expected to follow mostly constant values [2.1]. The exact forms of relationships between two sides of Equations (2.26) and (2.27) (i.e., linear, exponential, power, etc.) can only be obtained through experiments and it is expected that various shapes be obtained for each case depending on the vehicle, road, and the person to operate the vehicle [2.1].

2.5 PREDICTION ASSESSMENT METHODOLOGY OF ROAD

ENVIRONMENT FAILURE RATE

The road system, like any other complex socio-technical system, is constantly changing. Drivers must continuously make dynamic driving behavior in response to these changes in the road environment [2.1, 2.15]. The information conveyed by the road and road environment is essential for the driving and avoiding risky behaviors [2.1, 2.16, 2.17]. The road environment can be broken down to the following sets of components [2.1]:

- The physical components of roads like signs, lighting, markings, asphalts, guard rails, tunnels, bridges, etc. The failure rate of physical component j of road environment is shown by $\lambda_{e,i=1}(\text{Physical components of roads},j)$
- The atmosphere related factors in failure of roads for safe driving like snow, thunder storm, ice rain, quake, etc. The failure rate of atmosphere component j of road environment is shown by $\lambda_{e,i=2}(\text{atmosphere components of roads},j)$

The failures in the first group, that is, physical components are obtainable from the sources mentioned in Section 1.2.1. Furthermore, the failure rates in second group, that is, the atmosphere related factors causing the failure in roads (e.g., slippery roads, degraded driving visibility) can be estimated using past collected data regarding atmosphere conditions, road maintenance in such atmosphere conditions, reported accidents, reported car break downs, etc. and use of Monte Carlo simulations and experiments [2.1]. Consequently, the total failure rates of constituting physical and atmosphere components of roads can just be estimated with adding them up (i.e., $\lambda_E(t) = \sum_{j=1}^n \lambda_{e,i=1}(\text{Physical components of roads},j) + \sum_{j=1}^m \lambda_{e,i=2}(\text{atmosphere components of roads},j)$) under the conservative assumption that they are

all in series and in their useful life period [2.1]. Otherwise, the failure rate of each and every components of roads, λ_{ei} , regardless of the stage of their life period shall be fed to Equation (2.19) to predict the reliability and then the result needs to be fed to Equation (2.23) to obtain total failure rate of road environment, λ_E . With respect to distribution characteristics of road failure rate, λ_E , it is expected that its physical group of components, $\lambda_{ei=1}$ (*Physical components of roads*), to follow a bathtub pattern as illustrated in Fig. 2.3 (decreasing in infant-mortality period, constant in useful life period and increasing in wear-out period). However, the failure life pattern of roads due to atmosphere related group of components, $\lambda_{ei=2}$ (*atmosphere related components of roads*), requires experimentation, analysis and discussion by researchers [2.1].

2.6 PREDICTION ASSESSMENT METHODOLOGY OF DRIVER'S FAILURE RATE DUE TO NON-FATIGUE FACTORS

The human failure rate due to non-fatigue factors, λ_H , can be estimated taking into account all possible non-fatigue causes or components of human failure including skill, experience, driving behavior and conduct, health, alcohol/drug consumption, etc. [2.1]. The failure rate of driver due to each of these factors should be obtained from such sources as police reports, medical reports, experiments, simulators, etc. (e.g., [2.1, 2.18]). The reliability and total failure rate of human failure due to non-fatigue factors, λ_H , can be estimated using Equations (2.21) and (2.25) [2.1]. It is to be noted that the human failure rate due to experience and skill is expected to follow a pattern similar to bathtub curve shown in Figure 2.3 as this failure rate is reflection of drivers' skill, abilities and experience in their total driving life

span [2.1]. The first period, infant mortality period, would be representation of their learning period, the second period, useful life, is going to be representative of reaching a maturity and stability level in driving abilities and skill, and finally the last period, wear-out period, would be an indicative of their aging period which naturally the failure rate is expected to increase [2.1].

CHAPTER 3

RELIABILITY PREDICTION FOR THE VEHICLES EQUIPPED WITH ADVANCED DRIVER ASSISTANCE SYSTEMS (ADAS) AND PASSIVE SAFETY SYSTEMS (PSS)

3.1 BACKGROUND

The ADAS and PSS technologies are two approaches used in modern vehicles to mitigate the risk of accidents or casualties resulting from human error.

This research highlights and analyzes the safety features of ADAS and PSS in the design of road vehicles considering the demanding and tedious nature of operating a road vehicle which may pose drivers at the risk of committing error. The study proposes novel logical and mathematical modeling approaches to make assessment and prediction, at any instance of time, on the reliability of a modern vehicle composed of human as a driver, ADAS Warning System, ADAS Crash Avoidance System, and PSS.

The findings of the work are expected to be used in design and improvement of vehicles and utilized in safety assessment of road transportations and the development of new safety promotion policies, standards and methodologies by the transportation authorities and researchers.

3.2 THE RELIABILITY MODELING OF INTERFACE BETWEEN THE DRIVER, ADAS WARNING, AND ADAS CRASH AVOIDANCE AND

PASSIVE SAFETY SYSTEMS

Although the functional failure of the autonomous technologies in vehicles is remote (reliability over 98%), they might be tricked by complex and unexpected situations, whereas humans may be capable to resolve the problems when they are not susceptible to fatigue, distraction, and inattention [3.1].

In a typical vehicle, a driver applies the control systems in order to move the vehicle through the road environment, whereas in more advanced vehicles, two drivers (i.e., the human driver and the autonomous driver) could collaboratively control the vehicle [3.1]. All drivers experienced warnings from a passenger on a potential dangerous situation on roads; these warnings can save numerous lives every day [3.1]. Unlike other complex and potentially dangerous vehicles such as planes and ships, road vehicles are operated by a single person, whereas that person is prone to error and also slow to recognize potential hazards. A vehicle equipped with ADAS technologies as automated co-driver can double check life critical actions, relieve the driver of tedious activities, and warn about missed road events to improve the driver's reaction time and if necessary act autonomously to avoid crashes [3.1].

In a near future, all vehicles will be equipped with suitable ADAS technologies to save countless lives. Though, both active and passive safety systems remain vital in vehicles to protect lives in the event of driver's error [3.2].

Thus, the nature and sequence of interactions between the driver as vehicle operator, ADAS warning, ADAS crash avoidance system, and vehicle passive systems can be demonstrated by a stand-by Reliability Block Diagram (RBD) as shown in Fig. 3.1 (Model 1) [3.2]. This model represents a design in a way that once the driver fails to operate

the vehicle safely, the ADAS warning system gives necessary alarms to driver, the failure in ADAS warning leads to activation of ADAS Crash avoidance system and finally the failure in ADAS crash avoidance system results in activation of vehicle passive system (PSS) [3.2]. This model is macro level of the models 2-4 which are developed and presented hereinafter. The risks of accidents are expected to be lowest with this principle of design (i.e., modules in parallel) which remains same across four models presented here [3.2].

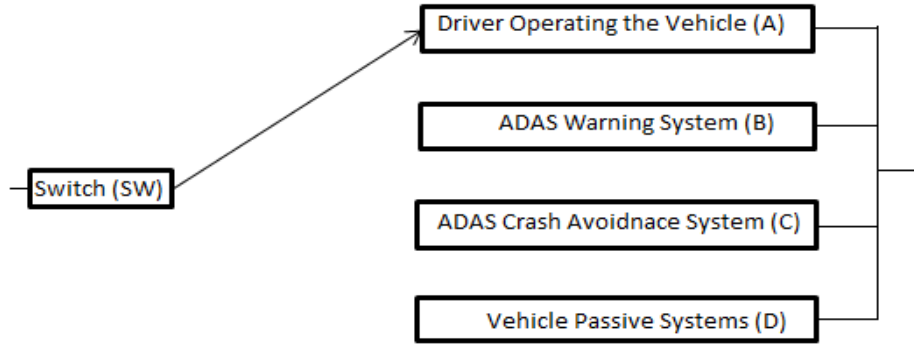


Figure 3.1-RBD of Stand-by System Composed of Uni-Component of Driver, Vehicle Equipped with ADAS Systems and Passive Systems (Model 1)

The reliability of such system composed of Driver, Active (ADAS Warning and ADAS Crash Avoidance Systems) and Passive safety systems as illustrated in Fig. 3.1 can be determined at any given time from Equation (3.1) [3.2].

$$\begin{aligned}
 \mathbf{R}_{system\ of\ Model\ 1} = & R_{switch-A\ to\ B} \cdot R_A(t) + \int_0^t f_A(x_A) \cdot R_{switch-A\ to\ B} \cdot R_B(t - \\
 & x_A) \cdot dx_A + \int_0^t f_A(x_A) \cdot \int_{x_A}^t f_B(x_B) \cdot R_{switch-B\ to\ C} \cdot R_C(t - x_A - x_B) \cdot dx_B \cdot dx_A + \\
 & \int_0^t f_A(x_A) \cdot \int_{x_A}^t f_B(x_B) \cdot \int_{x_B}^t f_C(x_C) \cdot R_{switch-C\ to\ D} \cdot R_D(t - x_A - x_B - x_C) \cdot dx_A \cdot dx_B \cdot dx_C \quad (3.1)
 \end{aligned}$$

It is to be noted that the methodology for developing ‘Model 1’ is going to remain the same for each potential stream of failures leading to an accident. It means that each type of human failure may trigger a certain type of ADAS warning, subsequently failure in that triggered ADAS warning is going to activate a certain ADAS crash avoidance system, and finally the failure in that activated ADAS crash avoidance system will lead to the activation of a particular passive safety system [3.2].

It should be mentioned that the human component in Model 1 can be split into mental and physical components in series in which the failure in each can result in failure of the driver [3.2]. Further, the ADAS warning and ADAS crash avoidance components in ‘Model 1’ can be decomposed to sub-systems in a series structure. With respect to Vehicle Passive Safety System in ‘Model 1’, this type of system in vehicles may contain several components in series that are all triggered by an incident in order to protect passengers (i.e., activation of air bag and advanced seatbelts) [3.2]. Thus, ‘Model 1’ (Fig. 3.1) can be transformed into a more micro level in form of stand-by parallel series model (Model 2) as depicted in Figure 3.2 [3.2].

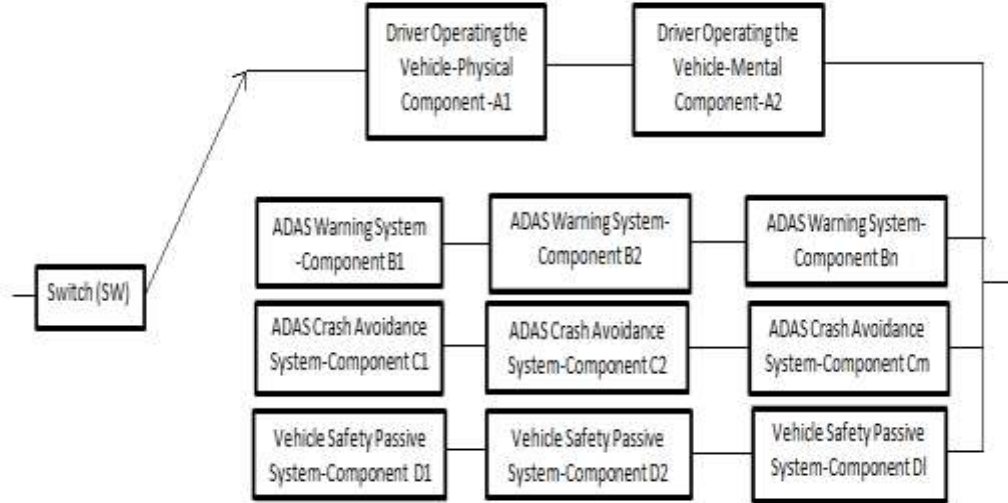


Figure 3.2-RBD of Stand-by System Composed of Multi-Components of Driver (Series), ADAS Warning Systems (Series), ADAS Crash Avoidance Systems (Series) & Passive Systems (Series) (Model 2)

Accordingly, the reliability estimation of ‘Model 2’ can be obtained from the following equation (Eq. 3.2) [3.2].

$R_{system\ of\ Model\ 2} =$

$$\begin{aligned}
 & R_{switch-A\ to\ B} \cdot R_{A1}(t) \cdot R_{A2}(t) + \sum_{i=1}^2 \left(\int_0^t f_{Ai}(x_{Ai}) \cdot R_{switch-A\ to\ B} \cdot \left(\prod_{j=1}^n R_{Bj}(t - \right. \right. \\
 & \left. \left. x_{Ai}) \right) dx_{Ai} \right) + \sum_{i=1}^2 \left(\sum_{j=1}^n \int_0^t f_{Ai}(x_{Ai}) \cdot \int_{x_{Ai}}^t f_{Bj}(x_{Bj}) \cdot R_{switch-B\ to\ C} \cdot \left(\prod_{k=1}^m R_{Ck}(t - \right. \right. \\
 & \left. \left. x_{Bj}) \right) \right) dx_{Bj} \cdot dx_{Ai} + \\
 & \sum_{i=1}^2 \left(\sum_{j=1}^n \left(\sum_{k=1}^m \int_0^t f_{Ai}(x_{Ai}) \cdot \int_{x_{Ai}}^t f_{Bj}(x_{Bj}) \cdot \int_{x_{Bj}}^t f_{Ck}(x_{Ck}) \cdot R_{switch-C\ to\ D} \cdot \prod_{l=1}^v R_{Dl}(t - \right. \right. \\
 & \left. \left. x_{Ai} - x_{Bj} - x_{Ck}) \right) \right) dx_{Ai} \cdot dx_{Bj} \cdot dx_{Ck} \quad (3.2)
 \end{aligned}$$

As Figure 3.3 illustrates the other potential design of a vehicle consisting of a driver, ADAS systems, and PSS can be consistent with the reliability block diagram of ‘Model 3’. In this model, the physical and mental components of a human as a driver remain in a series but the

other systems including ADAS Warning, ADAS Crash Avoidance and Passive Systems would be broken down to components in a parallel structure [3.2].

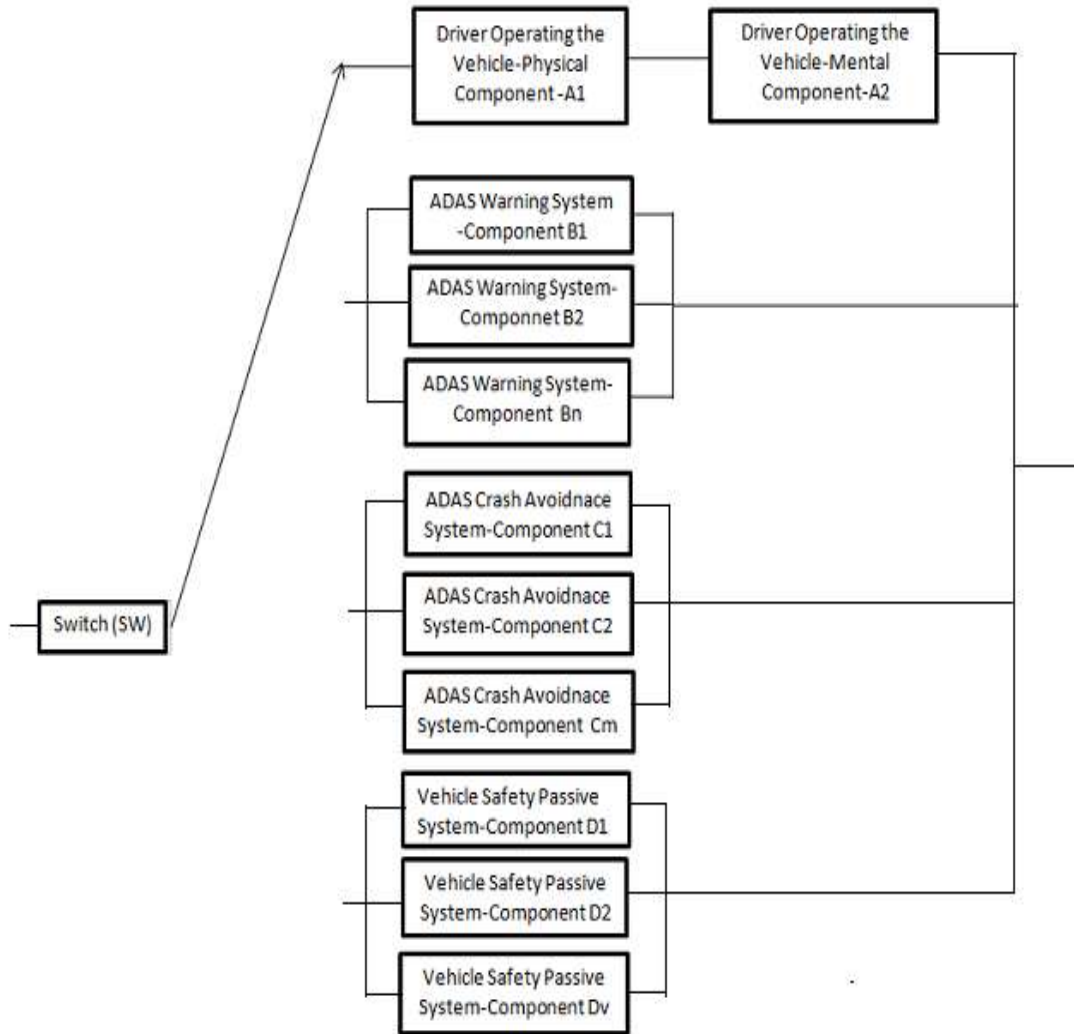


Figure 3.3-RBD of Stand-by System Composed of Multi-Components of Driver (Series), ADAS Warning Systems (Parallel), ADAS Crash Avoidance Systems (Parallel) & Passive Systems (Parallel) (Model 3)

The reliability value of such system as illustrated in Model 3 (Fig. 3.3) can be determined using Equation (3.3) [3.2].

$R_{\text{system of Model 3}} =$

$$\begin{aligned}
& R_{\text{Switch-A to B}} \cdot R_{A1}(t) \cdot R_{A2}(t) + \sum_{i=1}^2 \left(\left(\int_0^t f_{Ai}(x_{Ai}) \cdot R_{\text{Switch-A to B}} \cdot (1 - \prod_{j=1}^n (1 - \right. \right. \\
& \left. \left. R_{Bj}(t - x_{Ai})) dx_{Ai} \right) \right) + \sum_{i=1}^2 \left(\int_0^t f_{Ai}(x_{Ai}) \cdot \int_{x_{Ai}}^t \left(\prod_{j=1}^n f_{Bj}(x_{Bj}) \right) \cdot R_{\text{Switch-B to C}} \cdot (1 - \right. \\
& \left. \prod_{k=1}^m (1 - R_{Ck}(t - x_{Ai} - x_{Bj})) \right) dx_{Bj} \cdot dx_{Ai} + \\
& \sum_{i=1}^2 \left(\int_0^t f_{Ai}(x_{Ai}) \cdot \int_{x_{Ai}}^t \left(\prod_{j=1}^n f_{Bj}(x_{Bj}) \right) \cdot \int_{x_{Bj}}^t \left(\prod_{k=1}^m f_{Ck}(x_{Ck}) \right) \cdot R_{\text{Switch-C to D}} \cdot (1 - \right. \\
& \left. \prod_{l=1}^v (1 - R_{Dl}(t - x_{Ai} - x_{Bj} - x_{Ck})) \right) dx_{Ck} \cdot dx_{Bj} \cdot dx_{Ai}
\end{aligned} \tag{3.3}$$

Further expansion of Models 1-3 may lead to a most possible complex model as shown in Figure 3.4. In this model the human elements remains in series, whereas the constituting components of each of ADAS Warning, ADAS Crash Avoidance, and PSS modules are designed in parallel-series structure as presented in Model 4 [3.2]. However, the model constituting the above mentioned modules is designed in parallel in order to achieve greatest possible reliability in system [3.2].

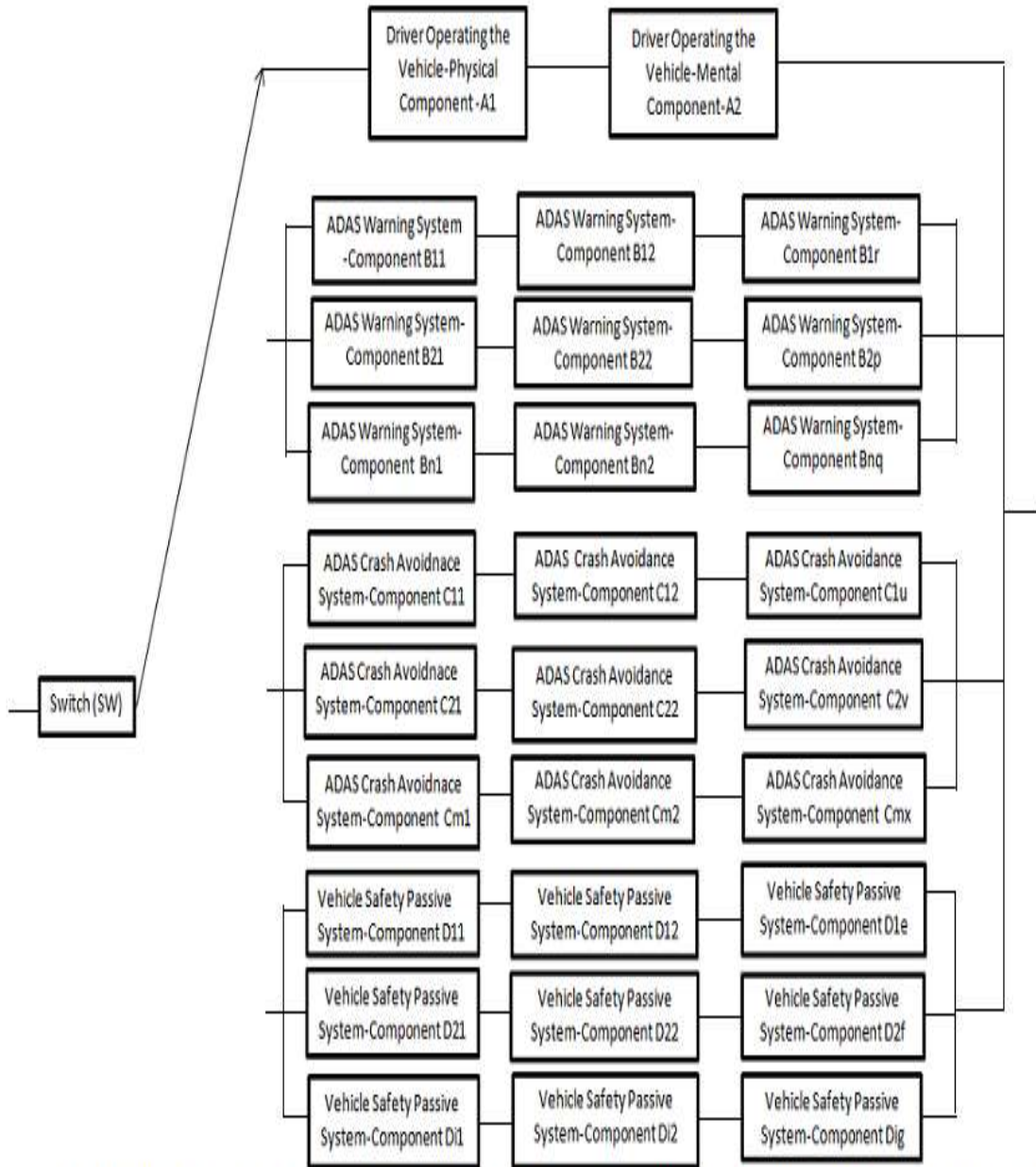


Figure 3.4-RBD of Stand-by System Composed of Multi-Components of Driver (Series), ADAS Warning Systems (Parallel-Series), ADAS Crash Avoidance Systems (Parallel-Series) & Passive Systems (Parallel-Series) (Model 4)

The Reliability of ‘Model 4’ as illustrated in Fig. 3.4 can be predicted from Equation (3.4) [3.2].

$R_{system\ of\ Model\ 4} =$

$$\begin{aligned}
& R_{Switch-A\ to\ B} \cdot R_{A1}(t) \cdot R_{A2}(t) + \sum_{i=1}^2 \left(\left(\int_0^t f_{Ai}(x_{Ai}) \cdot R_{Switch-A\ to\ B} \cdot \left(1 - \prod_{j=1}^n \left(1 - \right. \right. \right. \right. \\
& \left. \left. \left. \left. \prod_{p=1}^{r, \forall j=1; p, \forall j=2; \dots; q, \forall j=n} R_{Bjp}(t - x_{Ai}) \right) \right) \right) d_{x_{Ai}} \right) + \\
& \sum_{i=1}^2 \left(\int_0^t f_{Ai}(x_{Ai}) \cdot \int_{x_{Ai}}^t \left(\prod_{j=1}^n \left(\sum_{p=1}^{r, \forall j=1; p, \forall j=2; \dots; q, \forall j=m} f_{Bjp}(x_{Bjp}) \right) \right) \cdot R_{Switch-B\ to\ C} \cdot \left(1 - \right. \right. \\
& \left. \left. \prod_{k=1}^m \left(1 - \left(\prod_{d=1}^{u, \forall j=2; \dots; x, \forall j=n} R_{Ckd}(t - x_{Ai} - x_{Bj}) \right) \right) \right) \cdot dx_{Bj} \cdot dx_{Ai} + \\
& \sum_{i=1}^2 \left(\int_0^t f_{Ai}(x_{Ai}) \cdot \int_{x_{Ai}}^t \left(\prod_{j=1}^n \left(\sum_{p=1}^{r, \forall j=1; p, \forall j=2; \dots; q, \forall j=m} f_{Bjp}(x_{Bjp}) \right) \right) \cdot \right. \\
& \left. \int_{x_{Bj}}^t \left(\prod_{k=1}^m \left(\sum_{d=1}^{u, \forall j=2; \dots; x, \forall j=n} f_{Ckd}(x_{Ckd}) \right) \right) \cdot R_{Switch-C\ to\ D} \cdot \left(1 - \right. \right. \\
& \left. \left. \prod_{l=1}^y \left(1 - \prod_{p=1}^{e, \forall j=1; f, \forall j=2; \dots; g, \forall j=m} R_{Dlp}(t - x_{Ai} - x_{Bj} - x_{Ck}) \right) \right) dx_{Ai} \cdot dx_{Bj} \cdot dx_{Ck} \quad (3.4)
\end{aligned}$$

3.3 ILLUSTRATIVE EXAMPLE

A simple example of the application of ‘Model 4’ as the most complex form of models developed in this research, though the foundation of all four models are alike, is presented in Figure 3.5 [3.2]. In this example, the human fails to control the speed within safe limit due to mental or physical failure, as the result the visual and audio warnings are presented to the driver [3.2]. The failure in effectively controlling the speed with these warnings cause the activation of ADAS speed adjustor and braking systems subject to immediate danger detected by sensors. Finally, failures in the ADAS activation systems will result in activation of seatbelt and airbag systems as the last resort to protect the human casualties [3.2].

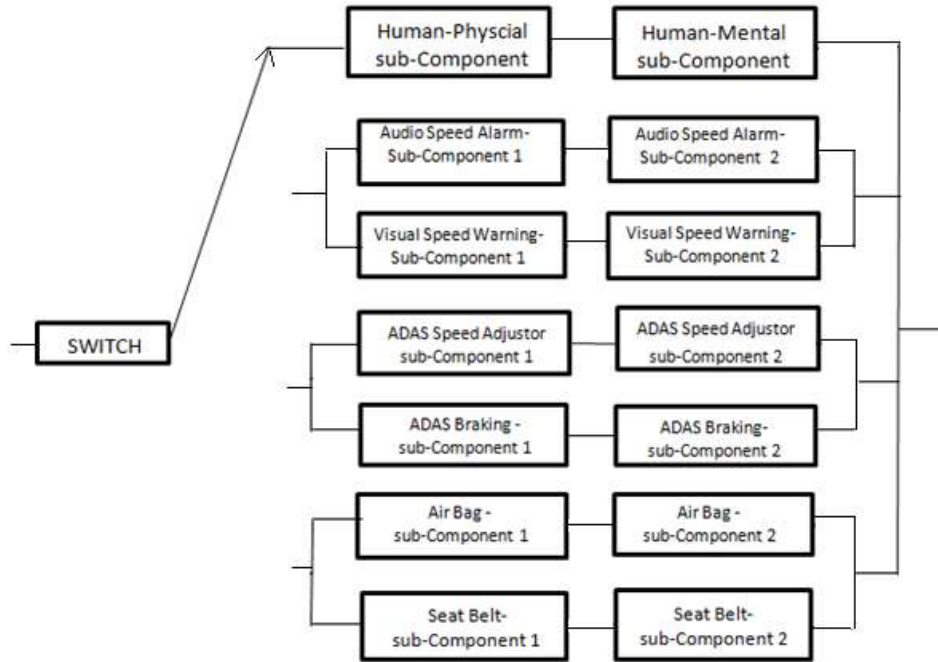


Figure 3.5-A Real Example of Model 4 as the Most Complex Models

It is to be noted that as the reliability of systems in a series structure is expected to be lower than that of a parallel structure when the number of components remains the same, thus the designers are expected to put the modules (i.e., Model 1-4) in parallel in relation to each other in order to enhance the safety of a system as much as possible [3.2]. As the result, the total reliability of a vehicle composed of a number of modules each similar to either of Models 1-4 can be estimated by Equation (3.5) [3.2]:

$$R_{Total} = 1 - \prod_{i=1}^n (1 - R_{System\ of\ Model\ i}) \quad (3.5)$$

CHAPTER 4

THE STOCHASTIC AND INTEGRATIVE PREDICTION METHODOLOGY AND MODELING FOR RELIABILITY OF PEDESTRIAN CROSSING ON ROADS

4.1 BACKGROUND

This research highlights the significance of pedestrians' safety across the world. Furthermore, it identifies the factors causing the human errors by drivers and pedestrians and then provides a logical and analytical qualitative model using fault tree to capture the sequence and interactions among factors causing pedestrian-to-vehicle accident. Subsequently, it proposes reliability prediction methodology and mathematical models to estimate the pedestrians' crossing reliability at any given time taking into account all relevant impacting factors or variables (e.g., pedestrian behavior, vehicles, environment, and road infrastructure). An example on how the models can be used has been given. Finally, it discusses the implications of the research in terms of theory and applications and provides some directions for further research works.

4.2 THE LOGICAL AND ANALYTICAL MODELING OF FACTORS CAUSING PEDESTRIAN-TO-VEHICLE ACCIDENTS ON ROADS

Probabilistic risk assessment (PRA) is a comprehensive and structured analytical methodology aimed at identifying and evaluating risks of complex process systems [4.1]

both quantitatively and qualitatively. PRA uses fault tree analysis (FTA) as a tool to illustrate basic causes and their dependencies leading to an undesired event, and to facilitate the risk calculation of occurring this event [4.1, 4.2]. FTA is widely used in reliability predictions and assessment of complex systems (e.g., nuclear reactor, aerospace application, petro chemical, oil and gas industries) [4.2, 4.3, 4.4].

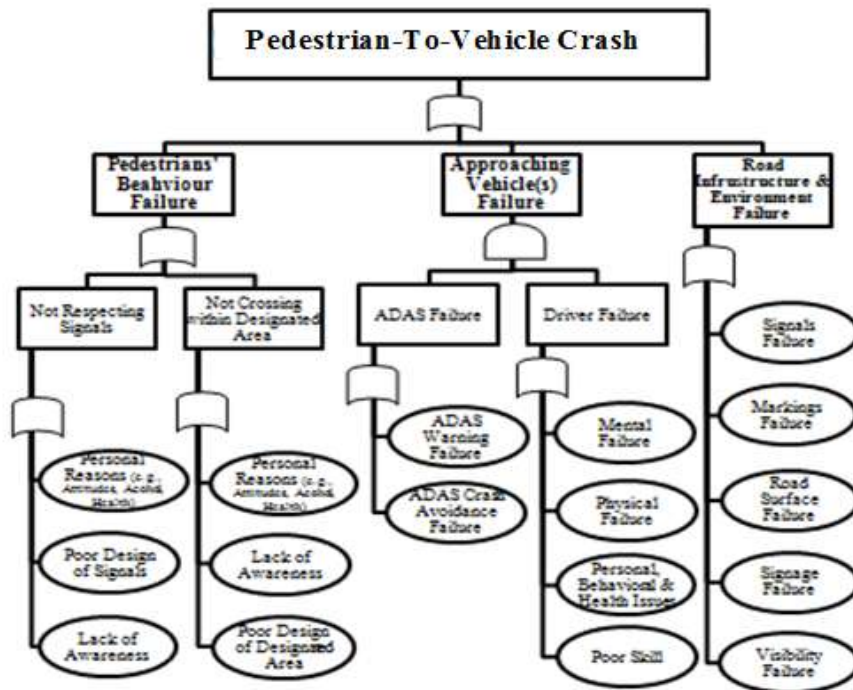


Figure 4.1-Fault Tree for Pedestrian Crossing

The author has developed a fault tree, as presented in Fig. 4.1, as a tool to capture and show the main and basic identified causes along with their dependencies in relation to the unwanted event of pedestrian-to-vehicle accidents [4.5]. Furthermore, Fig. 4.1 (fault tree) has been used to obtain the failure probability and reliability of the causes contributing to the safety of pedestrians and subsequently the occurrence risk of this accident [4.5].

4.3 THE RELIABILITY PREDICTION OF PEDESTRIAN-TO-VEHICLE ACCIDENTS

In previous sections, the factors causing pedestrian-to-vehicle accidents have been identified and modeled logically and illustratively in terms of their dependencies, sequence, and the conditions for leading to the undesired accident. In this section, the focus of research has been moving towards provision of the quantitative model in order to make prediction on the risk of occurring unwanted event of pedestrian-to-vehicle accident based on the developed fault tree (Fig. 4.1) [4.5].

To conduct a quantitative fault tree analysis, it is required to have a fault tree along with failure data for the basic events (i.e., causing components) [4.2]. The exact estimated values of the failure rates for components or the probability of occurrence of undesired events due to lack of sufficient data is often missing (or sparse) or is subject to imprecision [4.1, 4.2]. Thus, in this study due to its novelty in theme and approach, the prediction of failure or reliability of the components (i.e., vehicle, pedestrian and road infrastructure) causing the unwanted event of pedestrian-to-vehicle as depicted in Fig. 4.1 has been seen crucial [4.5].

4.3.1 RELIABILITY PREDICTION OF “VEHICLE EQUIPPED WITH ADAS” IN LIGHT OF PEDESTRIAN-TO-VEHICLE ACCIDENT

The author proposes that the interactions among components of vehicles equipped with ADAS Warning and ADAS Crash Avoidance Systems can best be modeled by a macro level Stand-by Reliability Block Diagram (RBD) as shown in Fig. 4.2 [4.5]. It is to be noted that the model presented in Fig. 4.2 can be transformed in reality into a complex model as

depicted in Fig. 4.3 [4.5]. Unlike the work done by [4.4], the models shown in Figs. 4.2 & 4.3 do not contain a box for the Passive Safety System as the focus of this research has been to protect pedestrians as the weakest road users and not drivers [4.5].

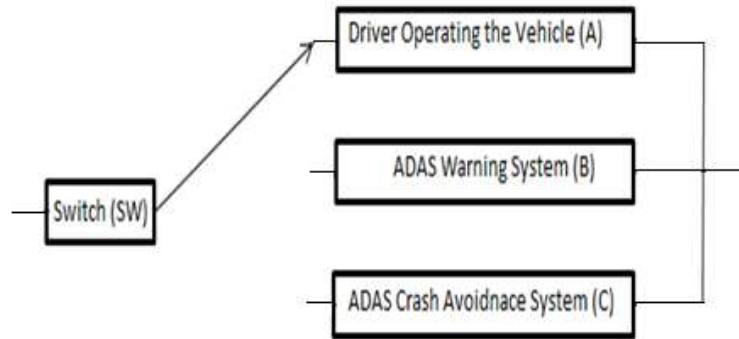


Figure 4.2-RBD of Stand-by System Composed of Uni-Component of Driver & Vehicle Equipped with ADAS Systems

Both Figs. 4.2 & 4.3 show that a vehicle is operated by driver until the driver fails to control it safely as per predefined specifications. The driver failure whether due to physical or mental factors triggers the activation of ADAS warning system, which may be composed of various components [4.5]. Subsequently, in the event of failure by ADAS warning system in returning the control of vehicle to a safe mode, the ADAS crash avoidance system, which may be composed of various components, is activated as the last resort to avoid crash with pedestrians [4.5].

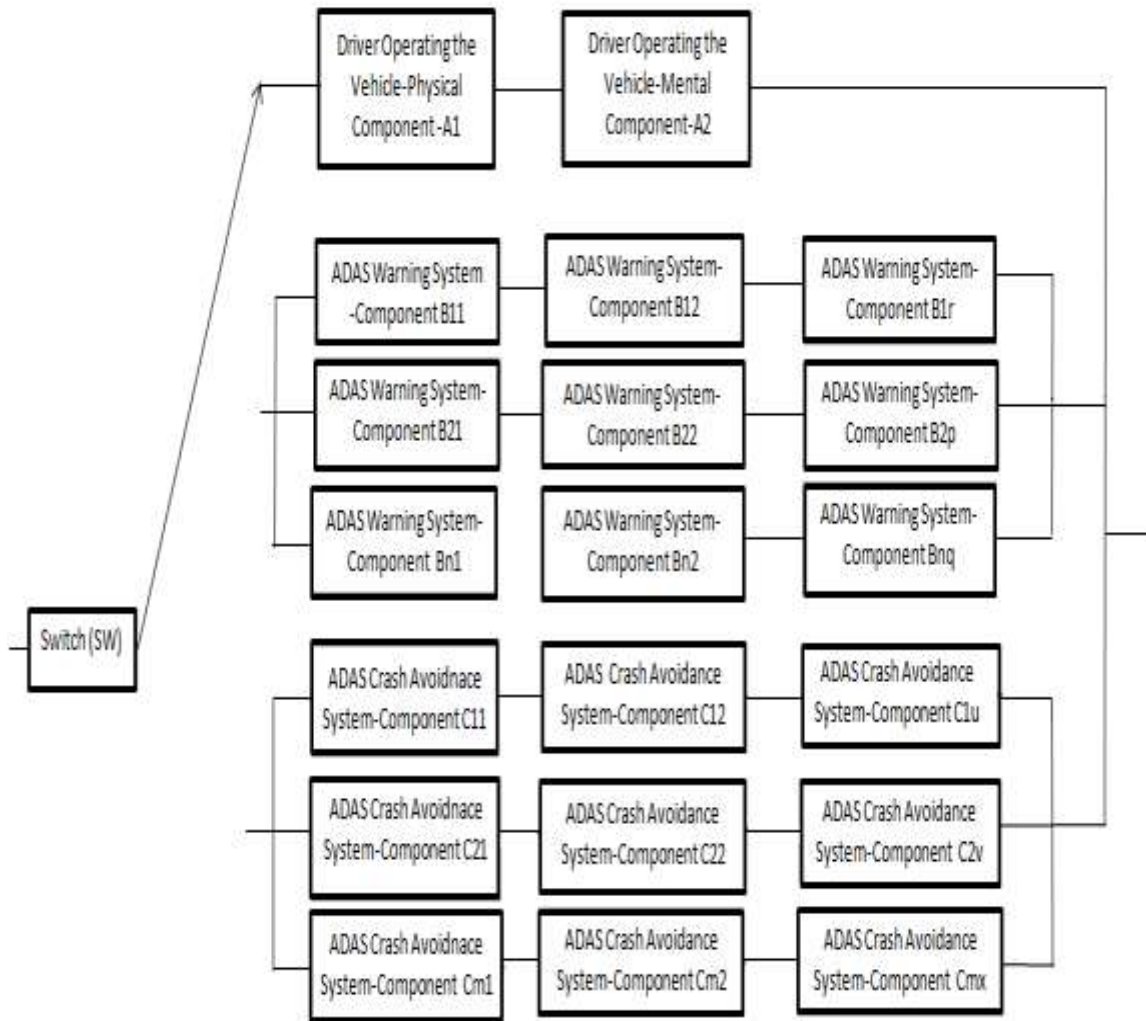


Figure 4.3-RBD of Stand-by System Composed of Multi-Components of Driver (Series), ADAS Warning Systems (Parallel-Series) & ADAS Crash Avoidance Systems (Parallel-Series)

Furthermore, it has been proposed that the reliability of a vehicle containing an individual module (Fig. 4.3) can be estimated by Eq. (4.1) [4.5]. However, in the event that a vehicle contains a set of individual modules, placed in parallel in relation to each other, in order to achieve maximum possible reliability, its reliability can be determined using Eq. (4.2) [4.5].

$$\begin{aligned}
R_{IM}(t) = & R_{A/B} \cdot R_{A1}(t) \cdot R_{A2}(t) + \sum_{i=1}^2 \left(\left(\int_0^t f_{Ai}(x_{Ai}) \cdot R_{A/B} \cdot \left(1 - \prod_{j=1}^n \left(1 - \right. \right. \right. \right. \\
& \left. \left. \left. \left. \prod_{p=1}^{r, \forall j=1; p, \forall j=2; \dots; q, \forall j=n} R_{Bjp}(t - x_{Ai}) \right) \right) \right) d_{x_{Ai}} \right) + \\
& \sum_{i=1}^2 \left(\int_0^t f_{Ai}(x_{Ai}) \cdot \int_{x_{Ai}}^t \left(\prod_{j=1}^n \left(\sum_{p=1}^{r, \forall j=1; p, \forall j=2; \dots; q, \forall j=n} f_{Bjp}(x_{Bjp}) \right) \right) \cdot R_{B/C} \cdot \left(1 - \right. \right. \\
& \left. \left. \prod_{k=1}^m \left(1 - \left(\prod_{d=1}^{u, \forall d=1; v, \forall d=2; \dots; x, \forall d=n} R_{Ckd}(t - x_{Ai} - x_{Bj}) \right) \right) \right) \cdot dx_{Bj} \cdot dx_{Ai} \quad (4.1)
\end{aligned}$$

$$R_{MPM}(t) = 1 - \prod_{i=1}^n (1 - R_{i,IM}(t)) \quad (4.2)$$

It is to be noted that though the models proposed above assume vehicles equipped with ADAS but this does not mean that these models do not work for vehicles without ADAS [4.5]. The reliability values obtained from the above proposed formulas shall be lower for vehicles with no or less advanced ADAS technologies than luxurious cars with fully equipped ADAS [4.5].

4.3.2. THE RELIABILITY PREDICTION OF “PEDESTRIAN CROSSING” AS THE RESULT OF PEDESTRIAN BEHAVIOR

The causes of pedestrian-to-vehicle accidents due to pedestrian behavior, derived from Fig. 4.1, can be grouped into three main groups including personal reasons, lack of awareness towards signals/crossing zone, and poor design of signals and crossing zone in light of human factors [4.5].

These three groups of constantly changing causes over the time would force or lead the pedestrian to make an accident causing error. The states of safe and unsafe pedestrian crossing on roads can be illustrated using Markov state diagram (Fig. 4.4) [4.5].

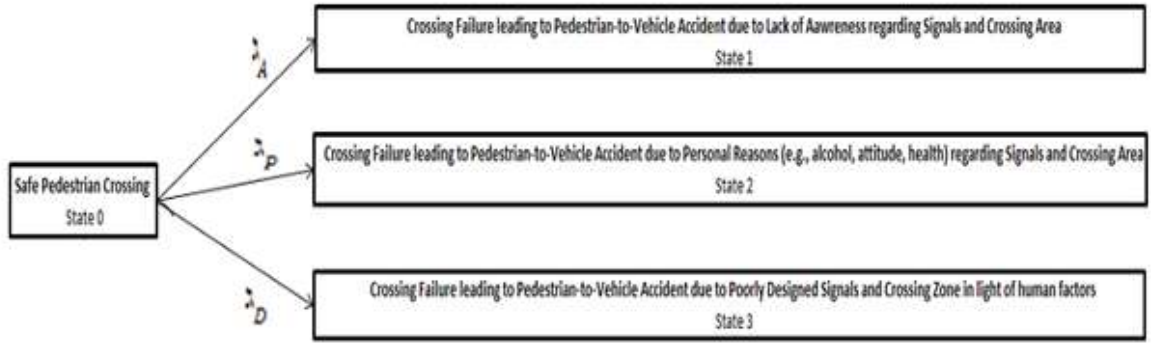


Figure 4.4-The Markov State Diagram for Pedestrian Crossing on Roads focusing on Pedestrian Behavior

Using the Markov method, Fig.4.4 can be converted into following stochastic mathematical modeling, Equations (4.3)-(4.6), in order to obtain the reliability or unreliability of pedestrian crossing due to pedestrian behavior and subsequently to use them in fault tree developed in Fig. 4.1 [4.5].

$$\frac{dP_0(t)}{dt} + (\lambda_A + \lambda_P + \lambda_D)P_0(t) = 0 \quad (4.3)$$

$$\frac{dP_1(t)}{dt} - (\lambda_A)P_0(t) = 0 \quad (4.4)$$

$$\frac{dP_2(t)}{dt} - (\lambda_P)P_0(t) = 0 \quad (4.5)$$

$$\frac{dP_3(t)}{dt} - (\lambda_D)P_0(t) = 0 \quad (4.6)$$

By taking Laplace transforms of Equations (4.3)-(4.6), solving them to obtain the equations for $P_0(s), P_1(s), P_2(s),$ and $P_3(s)$ and then taking inverse Laplace from the derived equations, the reliability function (Eq. (4.7)) and failure probability functions of pedestrian

crossing (Eqs. (4.8)-(4.10)) due to pedestrian behavior at any given time can be obtained [4.5]. Thus, we have [4.5]:

$$P_0^{PB}(t) = e^{-(\lambda_A + \lambda_P + \lambda_D)t} \quad (4.7)$$

$$P_1(t) = \frac{\lambda_A}{(\lambda_A + \lambda_P + \lambda_D)} (1 - e^{-(\lambda_A + \lambda_P + \lambda_D)t}) \quad (4.8)$$

$$P_2(t) = \frac{\lambda_P}{(\lambda_A + \lambda_P + \lambda_D)} (1 - e^{-(\lambda_A + \lambda_P + \lambda_D)t}) \quad (4.9)$$

$$P_3(t) = \frac{\lambda_D}{(\lambda_A + \lambda_P + \lambda_D)} (1 - e^{-(\lambda_A + \lambda_P + \lambda_D)t}) \quad (4.10)$$

4.3.3. THE RELIABILITY PREDICTION OF “PEDESTRIAN CROSSING” AS THE RESULT OF ROAD INFRASTRUCTURE & ENVIRONMENT

The causes of pedestrian-to-vehicle accidents due to road infrastructure and environment failure, derived from Fig. 4.1, can be grouped into five main groups: signals failure, marking failure, road surface failure, signage failure, and visibility failure [4.5].

These five groups of constantly changing causes over the time can force or lead the pedestrian to make an accident causing error. The states of safe and unsafe pedestrian crossing on roads as the result of road infrastructure and environment failure can be illustrated using Markov state diagram (Fig. 4.5) [4.5].

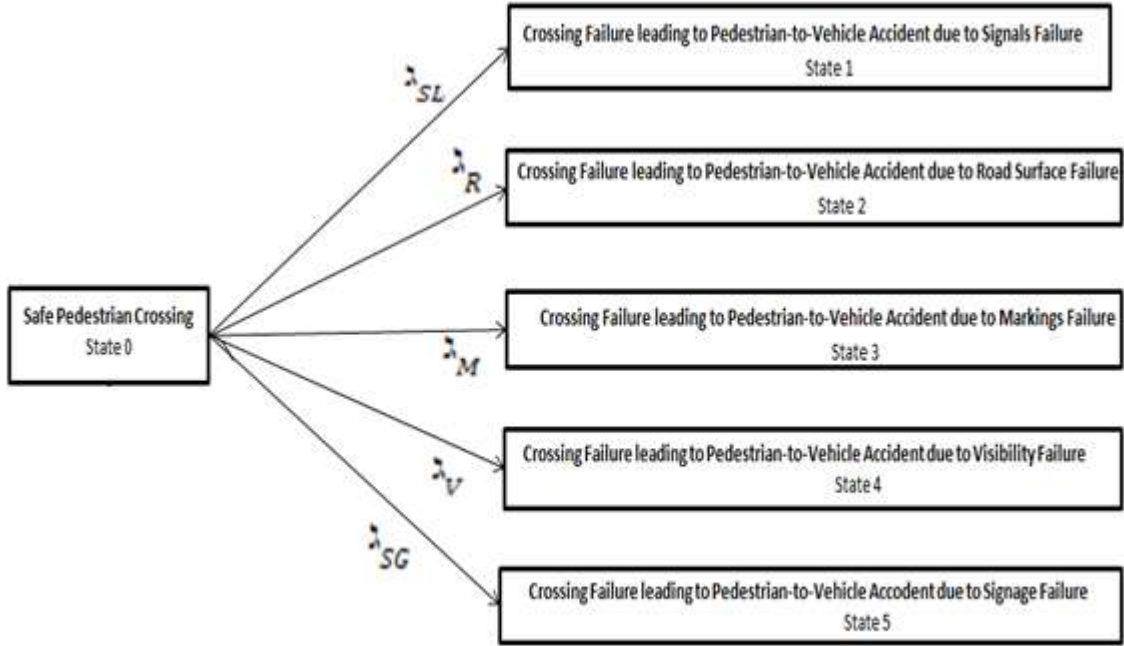


Figure 4.5-The Markov State Diagram for Pedestrian Crossing on Roads focusing on Pedestrian Infrastructure and Environment

Using the Markov method, Fig. 4.5 can be converted into differential equations (Eqs. (4.11)-(4.16)) in order to obtain the reliability or unreliability of pedestrian crossing due to road infrastructure and environmental factors [4.5]. Thus, we have [4.5]:

$$\frac{dP_0(t)}{dt} + (\lambda_{SL} + \lambda_V + \lambda_R + \lambda_M + \lambda_{SG})P_0(t) = 0 \quad (4.11)$$

$$\frac{dP_1(t)}{dt} - (\lambda_{SL})P_0(t) = 0 \quad (4.12)$$

$$\frac{dP_2(t)}{dt} - (\lambda_V)P_0(t) = 0 \quad (4.13)$$

$$\frac{dP_3(t)}{dt} - (\lambda_R)P_0(t) = 0 \quad (4.14)$$

$$\frac{dP_4(t)}{dt} - (\lambda_M)P_0(t) = 0 \quad (4.15)$$

$$\frac{dP_5(t)}{dt} - (\lambda_{SG})P_0(t) = 0 \quad (4.16)$$

By taking Laplace transforms of the above equations, solving them to obtain the equations for $P_0(s), P_1(s), P_2(s), P_3(s), P_4(s)$ & $P_5(s)$ and then taking inverse Laplace transforms of the derived equations, the reliability function (Eq. (4.17)) and failure probability functions of pedestrian crossing (Eqs. (4.18)-(4.22)) caused by road infrastructure and environmental factors at any given time can be obtained [4.5]. Thus, we have [4.5]:

$$P_0^{IE}(t) = e^{-(\lambda_{SL} + \lambda_V + \lambda_R + \lambda_M + \lambda_{SG})t} \quad (4.17)$$

$$P_1(t) = \frac{\lambda_{SL}}{(\lambda_{SL} + \lambda_V + \lambda_R + \lambda_M + \lambda_{SG})} \left(1 - e^{-(\lambda_{SL} + \lambda_V + \lambda_R + \lambda_M + \lambda_{SG})t}\right) \quad (4.18)$$

$$P_2(t) = \frac{\lambda_V}{(\lambda_{SL} + \lambda_V + \lambda_R + \lambda_M + \lambda_{SG})} \left(1 - e^{-(\lambda_{SL} + \lambda_V + \lambda_R + \lambda_M + \lambda_{SG})t}\right) \quad (4.19)$$

$$P_3(t) = \frac{\lambda_R}{(\lambda_{SL} + \lambda_V + \lambda_R + \lambda_M + \lambda_{SG})} \left(1 - e^{-(\lambda_{SL} + \lambda_V + \lambda_R + \lambda_M + \lambda_{SG})t}\right) \quad (4.20)$$

$$P_4(t) = \frac{\lambda_M}{(\lambda_{SL} + \lambda_V + \lambda_R + \lambda_M + \lambda_{SG})} \left(1 - e^{-(\lambda_{SL} + \lambda_V + \lambda_R + \lambda_M + \lambda_{SG})t}\right) \quad (4.21)$$

$$P_5(t) = \frac{\lambda_{SG}}{(\lambda_{SL} + \lambda_V + \lambda_R + \lambda_M + \lambda_{SG})} \left(1 - e^{-(\lambda_{SL} + \lambda_V + \lambda_R + \lambda_M + \lambda_{SG})t}\right) \quad (4.22)$$

4.3.4. THE RELIABILITY AND FAILURE PROBABILITY PREDICTION OF PEDESTRIANS CROSSING ON ROADS

The author proposes that the reliability of “pedestrian crossing” can be determined from Eqs. (4.23 & 4.24) using the illustrated fault tree (Fig. 4.1) [4.5].

$$R_{VUM}(t) = (Eq. (4.7)) \times (Eq. (4.17)) \times \left(\prod_{ve\ no=1}^{ve\ no=veh} Eq. (4.1_{ve\ no})\right) \quad (4.23)$$

$$R_{VMM}(t) = (Eq. (4.7)) \times (Eq. (4.17)) \times \left(\prod_{ve\ no=1}^{ve\ no=veh} Eq. (4.2_{ve\ no})\right) \quad (4.24)$$

It is to be noted that Equations (4.23) and (4.24) have incorporated the fact that a pedestrian may be in danger of being hit by excess of one vehicle depending on the type and capacities of roads (i.e., index of “*ve no*” denotes the number of approaching vehicles varying from 1 to the quantity of “*veh*”) [4.5].

Subsequently, the failure probability of pedestrian crossing on roads can be estimated from Equations (4.25) & (4.26) [4.5].

$$F_{VUM}(t) = 1 - Eq. (4.23) \quad (4.25)$$

$$F_{VMM}(t) = 1 - Eq. (4.24) \quad (4.26)$$

4.4 NUMERICAL EXAMPLE

In this section, the author has provided a numerical example on how the methodology developed in this chapter can be applied to predict the reliability of safe pedestrian crossing over the course of a specified time period.

The reliability values for “pedestrian crossing” affected by “pedestrian behavior” (Eq. (4.7)) and “road infrastructure/environment” (Eq. (4.17)) with the following hypothetical values and assumption of exponential distributions can be obtained as shown in Equations (4.27) & (4.28); respectively [4.5].

Hypothetical Values of Failure Rates for Pedestrian Behavior & Crossing Infrastructure:

$$\lambda_A = 0.002 \text{ failures/hr}$$

$$\lambda_P = 0.006 \text{ failures/hr}$$

$$\lambda_D = 0.0001 \text{ failures/hr}$$

$$\lambda_{SL} = 0.0003 \text{ failures/hr}$$

$$\lambda_{SG} = 0.0001 \text{ failures/hr}$$

$$\lambda_R = 0.0007 \text{ failures/hr}$$

$$\lambda_M = 0.0003 \text{ failures/hr}$$

$$\lambda_V = 0.0002 \text{ failures/hr}$$

$$t = 12 \text{ hrs}$$

$$P_0^{PB}(12\text{hrs}) = e^{-(0.002+0.006+0.0001) \times 12} = 90.737\% \quad (4.27)$$

$$P_0^{IE}(12\text{hrs}) = e^{-(0.0003+0.0001+0.0007+0.0003+0.0002) \times 12} = 98.098\% \quad (4.28)$$

Furthermore, the estimated reliability value for “pedestrian crossing” affected by an approaching “vehicle” (equipped with certain ADAS components as shown in Fig. 4.6 with the given hypothetical values) has been shown in Eq. (4.29) using Eq. (4.1). The assumptions of exponential distributions and a single standby RBD module (Fig. 4.3) have been held [4.5].

As per Fig. 4.6, the driver fails to control the speed within safe limit due to mental and/or physical failure, as the result the ADAS warnings (Audio/Visual) are presented to him/her. The failure in effectively controlling the speed despite these warnings would cause the activation of ADAS speed adjustor and subsequently the ADAS braking system, if necessary [4.5].

Hypothetical Values of Failure Rates for Vehicle & Driver Components in Fig. 4.6:

$$q_1(\text{Failure Rate of Driver's Physical Component}) = 0.005 \text{ failures/hr,}$$

$$q_2(\text{Failure Rate of Driver's Mental Component}) = 0.005 \text{ failures/hr,}$$

$$p_1(\text{Failure Rate of ADAS Audio Speed Alarm Component 1}) = 0.0005 \text{ failures/hr,}$$

$$p_2(\text{Failure Rate of ADAS Audio Speed Alarm Component 2}) = 0.0005 \text{ failures/hr,}$$

$$p_3(\text{Failure Rate of ADAS Visual Speed Alarm Component 1}) = 0.0004 \text{ failures/hr,}$$

$$p_4(\text{Failure Rate of ADAS Visual Speed Alarm Component 2}) = 0.0004 \text{ failures/hr,}$$

$$m(\text{Failure Rate of Switch A – B}) = 0.0004 \text{ failures/hr,}$$

$$n(\text{Failure Rate of Switch B – C}) = 0.0004 \text{ failures/hr,}$$

$$u_1(\text{Failure Rate of ADAS Speed Adjustor Component 1}) = 0.0003 \text{ failures/hr,}$$

$$u_2(\text{Failure Rate of ADAS Speed Adjustor Component 2}) = 0.0003 \text{ failures/hr,}$$

$$u_3(\text{Failure Rate of ADAS Braking System Component 1}) = 0.0002 \text{ failures/hr,}$$

$$u_4(\text{Failure Rate of ADAS Braking System Component 2}) = 0.0002 \text{ failures/hr}$$

$$R_{IM}(12 \text{ hrs}) = 99.979\% \quad (4.29)$$

Subsequently, the reliability of “pedestrian crossing” in light of safety under assumption of single approaching vehicle has been shown in Eq. (4.30) using Eq. (4.23) and the above obtained results [4.5].

$$R_{VUM}(12 \text{ hours}) = 0.90737 \times 0.98098 \times 0.99979 = 88.992\% \quad (4.30)$$

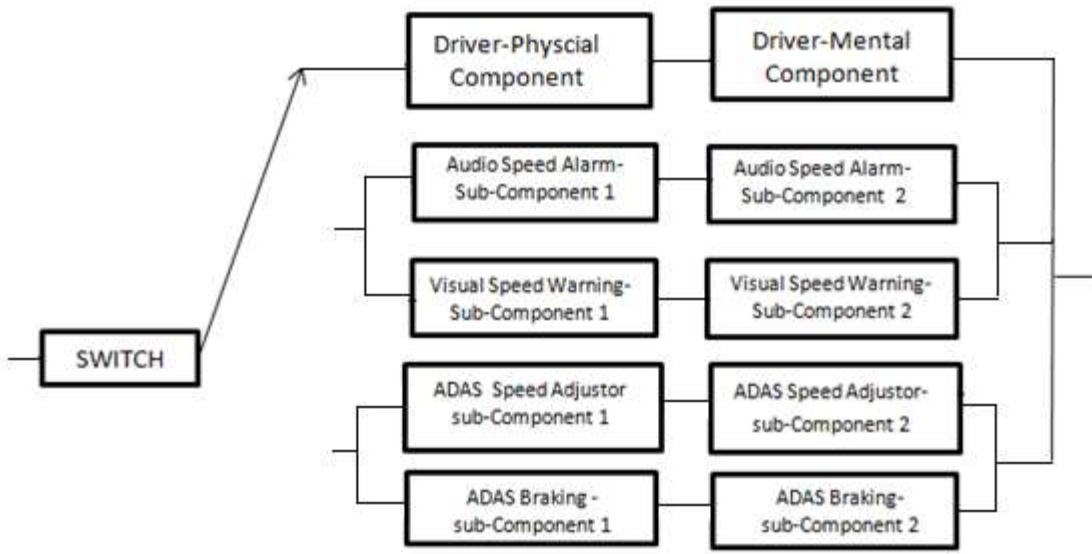


Figure 4.6-RBD of a Hypothetical Vehicle with ADAS Warning and Crash Avoidance System

CHAPTER 5

THE FTA's CONSTRAINED BASED METHODOLOGY IN RISK ASSESSMENT OF CRASH AND CONDITION MONITORING FOR OLDER DRIVERS ON ROADS

5.1 BACKGROUND

Over the years research has highlighted the high growth rate of older population in most societies and emphasized on the vital universal need of mobility by everyone whether young or old. The author has identified and discussed the limitations and strengths of older drivers in terms of driving abilities and behavior. The available measures to enhance the safety of older drivers have then been elaborated. Furthermore, the potential causes in risk of a crash by older drivers have been identified and modeled systematically and logically using fault tree analysis (FTA) to illustrate their dependencies and roles in relation to the occurrence of crash as unwanted event by older drivers. The author has gone on highlighting and mathematically modeling the fact that the human involved causes of the crash not only have their own individual characteristics and failure points but due to their interactive and accumulative effects on each other, they can fail in different points as the human elements are ultimately all parts of a centrally linked system.

The new in-vehicle technologies and their interfaces with drivers are expected to be built and modified based on the author's proposed methodology in order to constantly assess the older drivers' state and reduce the risk of crash by taking appropriate measures.

5.2 THE FTA OF OLDER DRIVERS FAILURE LEADING TO SEVERE CRASH

Traffic is to be considered as the result of interactions between people, vehicles and road infrastructure and the human in this process is the key and weakest element [5.1].

Logic diagram such as fault tree analysis (FTA) [5.2], master logic diagram [5.3], reliability networks [5.2, 5.4] is a risk analysis technique to assess system safety and reliability both qualitatively and quantitatively [5.5, 5.6].

The fault tree of older drivers causing crash with severe consequence has been developed as shown in Figure 5.1 [5.7].

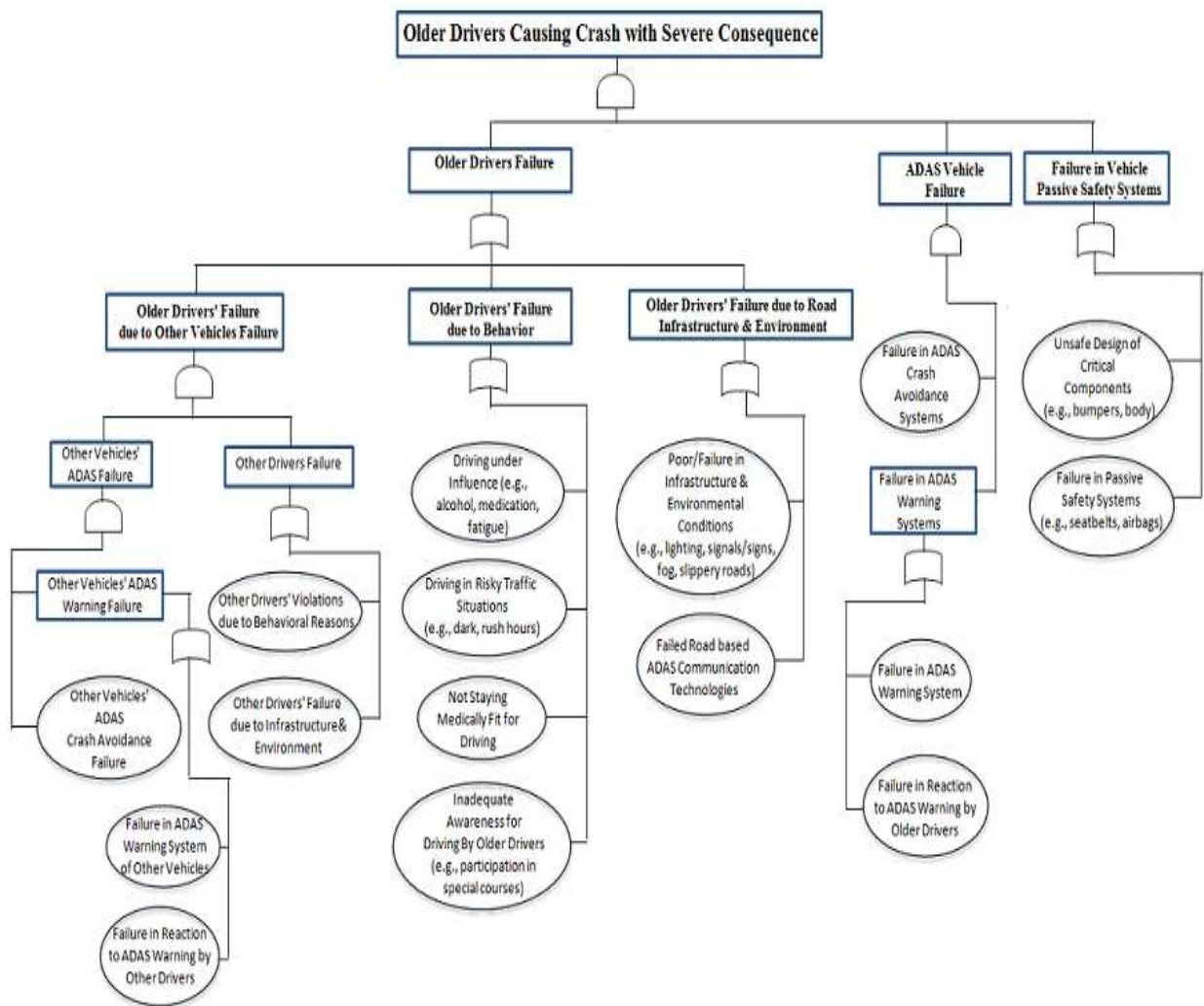


Figure 5.1-FTA of Older Drivers Causing Crash with Severe Consequence

Figure 5.1 illustrates and elaborates on the root causes of older drivers involved crash leading to casualty and their dependencies in relation to this unwanted event using FTA's symbols and construction principles [5.7]. The FTA's construction and analyses require both top-down and bottom-up approach. The causes of this unwanted event are categorized into three main groups: "Older Drivers related Causes", "ADAS Vehicle related Causes", and "Passive Safety related Systems" [5.7]. Subsequently, each of these three groups of causes are broken down into the intermediate and basic causes. The gate symbols are used to define the dependencies and relationships with each other.

5.3 THE INTEGRATION OF CONDITION MONITORING METHODOLOGY INTO THE DEVELOPED FTA FOR OLDER DRIVERS

The recent improvements in software and hardware components have led to the increased reliability of the machine component of a system, while the human component of system still remains unreliable [5.8, 5.9]. Machines could take limited options during their operation as per their design [5.8], whereas human is unpredictable, thus analysis of the human component of a system is significantly more difficult than its machine components [5.10].

There may be components in a complex system (e.g., human component), through which its performance can gradually be degraded with varying degree of severity and type [5.7]. Furthermore, the human involved causal events in failure of a system can be constantly under accumulative effects from each other as they are all linked parts of system called human [5.7]. Hence, human may fail to perform the task safely either as the result of failure in a single of human-based-causal events or a combination of human-based-causal

events [5.7]. To reflect these aforementioned characteristics of human based causal events, the FTA (Fig. 5.1) has been transformed to the Condition-based FTA for older drivers on roads as shown in Figure 5.2 [5.7].

Figure 5.2 complements Figure 5.1 such that the conditions (numbered 1 to 5) relating to human workload also define the likely occurrence of human involved causes either directly or through their affecting gate symbols [5.7].

As represented by Eqs. (5.1)-(5.5) (i.e., the conditions in Fig. 5.2), it is assessed whether or not the total of weighted physical and cognitive load(s) imposed on the driver depending on the situation is lower than the ultimate human capacity available to safely deal with the driving situations [5.7]. It is to be noted that the workloads are categorized into two groups: physical and cognitive. The former deals with any load imposed on the musculoskeletal system of human as the result of driving (e.g., fatigue on joints, muscles and spine due to physical stress or lack of mobility) and the latter refers to the load imposed on the sensual and perceptual channels and mechanisms of the older driver as the result of driving (e.g., mental fatigue due to constant and complex information processing by the older drivers with aged cognitive capacities and abilities) [5.7].

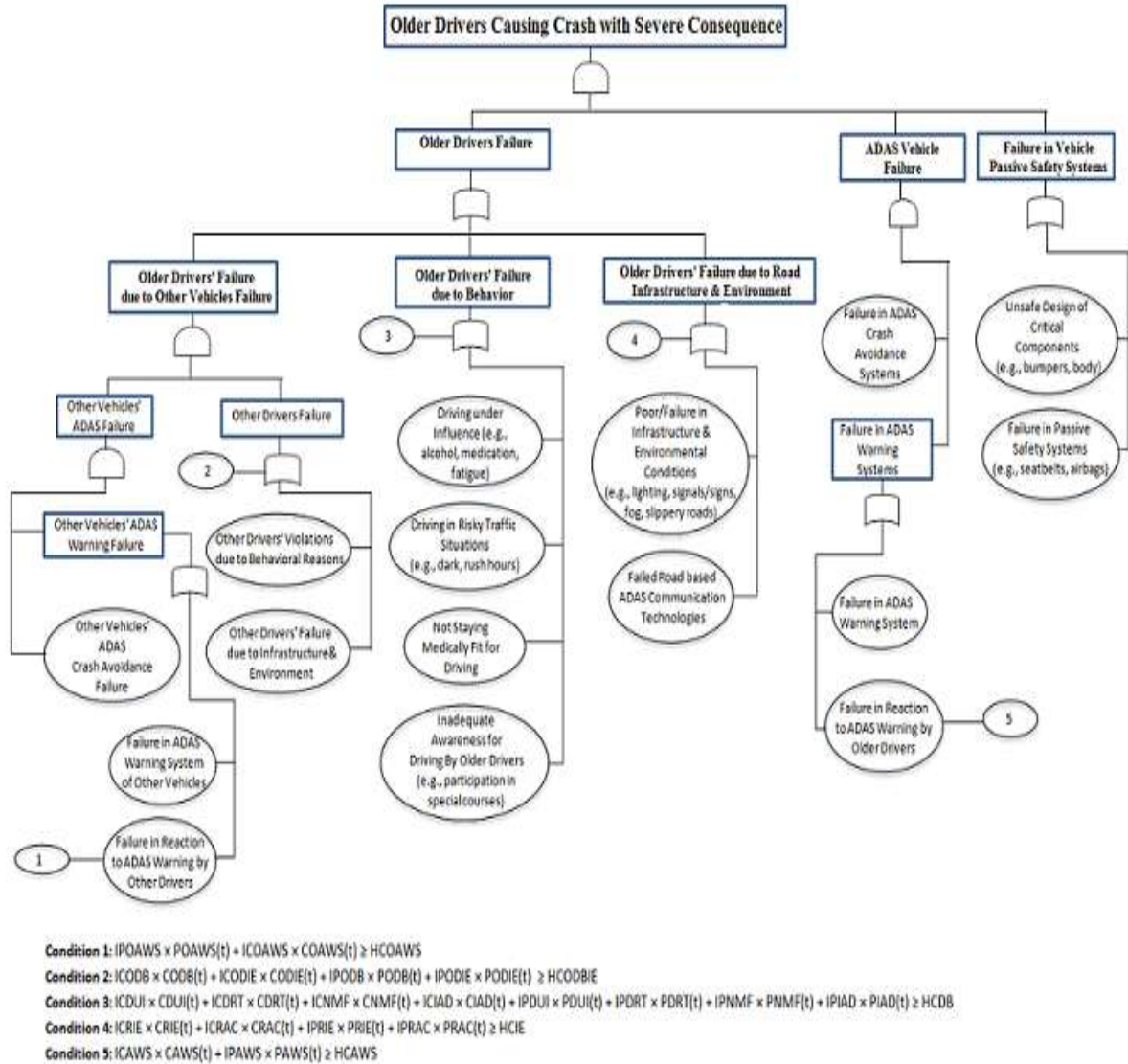


Figure 5.2-Conditioned-based-FTA of Older Drivers Causing Crash with Severe Consequence

$$\text{Condition 1: } IP_{OAWS} \times P_{OAWS}(t) + IC_{OAWS} \times C_{OAWS}(t) \geq HC_{OAWS} \quad (5.1)$$

$$\text{where, } IP_{OAWS} + IC_{OAWS} = 1; 0 \leq P_{OAWS}(t) \leq 100 + a; 0 \leq C_{OAWS}(t) \leq 100 + b; HC_{OAWS} = 100$$

Condition 2: $IC_{ODB} \times C_{ODB}(t) + IC_{ODIE} \times C_{ODIE}(t) + IP_{ODB} \times P_{ODB}(t) + IP_{ODIE} \times P_{ODIE}(t) \geq HC_{ODBIE}$ (5.2)

where, $IC_{ODB} + IC_{ODIE} + IP_{ODB} + IP_{ODIE} = 1; 0 \leq C_{ODB}(t) \leq 100 + c; 0 \leq C_{ODIE}(t) \leq 100 + d; 0 \leq P_{ODB}(t) \leq 100 + e; 0 \leq P_{ODIE}(t) \leq 100 + f; HC_{ODBIE} = 100$

Condition 3: $IC_{DUI} \times C_{DUI}(t) + IC_{DRT} \times C_{DRT}(t) + IC_{NMF} \times C_{NMF}(t) + IC_{IAD} \times C_{IAD}(t) + IP_{DUI} \times P_{DUI}(t) + IP_{DRT} \times P_{DRT}(t) + IP_{NMF} \times P_{NMF}(t) + IP_{IAD} \times P_{IAD}(t) \gg HC_{DB}$ (5.3)

where, $IC_{DUI} + IC_{DRT} + IC_{NMF} + IC_{IAD} + IP_{DUI} + IP_{DRT} + IP_{NMF} + IP_{IAD} = 1; 0 \leq C_{DUI}(t) \leq 100 + g; 0 \leq C_{DRT}(t) \leq 1 + h; 0 \leq C_{NMF}(t) \leq 100 + i; 0 \leq C_{IAD}(t) \leq 100 + j; 0 \leq P_{DUI}(t) \leq 100 + k; 0 \leq P_{DRT}(t) \leq 100 + l; 0 \leq P_{NMF}(t) \leq 100 + m; 0 \leq P_{IAD}(t) \leq 100 + n; HC_{DB} = 100$

Condition 4: $IC_{RIE} \times C_{RIE}(t) + IC_{RAC} \times C_{RAC}(t) + IP_{RIE} \times P_{RIE}(t) + IP_{RAC} \times P_{RAC}(t) \geq HC_{IE}$ (5.4)

where, $IC_{RIE} + IC_{RAC} + IP_{RIE} + IP_{RAC} = 1; 0 \leq C_{RIE}(t) \leq 100 + p; 0 \leq C_{RAC}(t) \leq 100 + q; 0 \leq P_{RIE}(t) \leq 100 + r; 0 \leq P_{RAC}(t) \leq 100 + s; HC_{IE} = 100$

$$\mathbf{Condition\ 5: } IC_{AWS} \times C_{AWS}(t) + IP_{AWS} \times P_{AWS}(t) \geq HC_{AWS} \quad (5.5)$$

$$\text{where, } IC_{AWS} + IP_{AWS} = 1; 0 \leq C_{AWS}(t) \leq 100 + u; 0 \leq P_{AWS}(t) \leq 100 + v; HC_{AWS} = 100$$

Workload is considered as the demand imposed upon people as the cost of accomplishing task requirements for the human component of a system [5.11, 5.12]. Furthermore, workload can lower the alertness and vigilance of human and adversely impact the concentration and increase the time for processing information and decision making with the increased likelihood of errors leading to accidents [5.13, 5.14, 5.15]. The workload assessment techniques are categorized [5.16]: (a) performance-based measures, (b) subjective measures, and (c) physiological measures.

As shown in Eqs. (5.1)-(5.5), the human capacity values on the right side of equations are set hypothetically equal to 100 just as the human capacity threshold for likely occurrence of critical failure by the driver [5.7]. The values of variables on the left side of equations can then be determined as any values at any given time within the set limits given in Eqs. (5.1)-(5.5) [5.7].

Each of Eqs. (5.1)-(5.5) refers to a condition introduced and integrated in the developed fault tree (i.e., Fig. 5.2) to obtain the total workload (i.e., both cognitive and physical) imposed on the older driver, as the result of an individual or a combination of human involved cause(s) and to compare it with the human capacity at any given time [5.7]. It is to be noted that the workload is accumulated over time, thus it is expected that the

workload imposed on the driver at the start of driving (i.e., time 0) to be lower than workload of his/her after some time of driving (i.e., 0+t) [5.7]. The equations although at a glance appear to be assessing the workload of the driver separately, depending on different sets of human involved causes as shown in Eqs. (5.1)-(5.5) [5.7]. However, it is to be noted that due to accumulative nature of human workload, the workloads calculated and shown in the developed conditions affect the other conditions indirectly [5.7]. Thus, the workload imposed on driving (e.g., due to driving under influence) affects the assessed workload imposed by the other individual or combination of human involved causes (e.g., road ADAS), that is, these are accumulated linearly or in different forms or shapes [5.7]. Subsequently, when the driver workload for each condition is measured through subjective or objective assessments, the effects of workload from other conditions are taken into account naturally and automatically [5.7].

The *impact factor* constants are introduced into Eqs. (5.1)-(5.5) in order to put weights on the variables located in left side of each condition depending on their significance in relation to each other [5.7]. The procedure for assignment of values for impact factor constants can be regulated by the transportation authorities based on the findings and recommendations of this research and future ones [5.7]. The values should be set and adjusted periodically by the auto industries/authorized auto dealership based on the degree of significance of each individual variable on left side of the conditions and the assessment by the transportation authorities on health and performance condition of each and every older driver [5.7].

The a to v constants are introduced into Eqs. (5.1)-(5.5) in order to let the total value of left side of conditions exceed proportionally from their right side value (i.e., human

capacity) subject to criticality degree of each individual workload variable in the left side of equations [5.7]. Some of the variables like cognitive workload caused by driving under influence (e.g., unacceptable level of alcohol consumption) can reach serious and critical level for some of the drivers to make driving highly hazardous [5.7]. Thus, the a to v constants would allow the ADAS to warn drivers and react in accordance with magnitude of difference between the values of left and right sides of conditions [5.7]. The procedure for assignment of values for a to v constants similar to impact factors as described in previous paragraph can be regulated, set, and adjusted [5.7].

However, the physical and cognitive workload related variables affected by the situations/systems shall be determined by the objective or subjective assessments of the users (i.e., drivers) at any given time [5.7]. Some of the workload assessments in relation to those human involved events, as identified in Fig. 5.2, can be done objectively (i.e., performance and physiological assessment based methods) through already available in vehicle technologies (e.g., vigilance monitoring system, alcohol detection system, and speed limit warning) [5.7]. The other required assessments of workload influenced by factors such as fatigue or boredom can be done using periodic or on-demand subjective input from drivers while driving [5.7, 5.17, 5.18]. The subjective input from drivers can be fed by means of voice [5.19] or touch into the in-vehicle technologies equipped with software built based on author's developed methodology to assess and check at any given time the mathematical conditions represented by Eqs. (5.1)-(5.5) [5.7]. Both objective and subjective assessments of driver in light of workload shall be converted into the corresponding scales as per Eqs. (5.1)-(5.5) [5.7].

5.4 ILLUSTRATIVE EXAMPLE

It has been illustrated in the following how condition 3 of Fig. 5.2 can be applied for an older driver with certain hypothetical degrees of suitability/unsuitability in relation to the constituting elements of the condition [5.7]. This older driver in this example is considered to be in typically accepted age group of older drivers (i.e., over 65 years) with his/her own unique behavioral and medical characteristics and with specific driving awareness and record [5.7].

Risky driving attitude:

As per live assessments by in vehicle technologies (e.g., lane departure warning, adaptive cruise control, collision warning and avoidance, and road based speed deviation detector) on risky driving state of the driver at a given time (e.g., in minute 45 of driving), the scores of 110 and 70 out of 120 for cognitive and physical workload placed on the driver are assigned as the result of his/her risky driving state, respectively (i.e., 0 is most suitable and 120 is least suitable) [5.7]. The initial values for IC_{DRT} and IP_{DRT} have been set by auto industries 0.20 and 0.05, respectively [5.7].

Not medically fit for driving:

As per last periodic assessment on medical state of the driver and requirements in light of safe driving, the authorities decided to assign scores of 70 and 60 out of 100 for cognitive and physical workload placed on the driver while driving as the result of his/her medical state, respectively (i.e., 0 is most suitable and 100 is least suitable) [5.7]. The initial values for IC_{NMF} and IP_{NMF} have been set by auto industries 0.20 and 0.10, respectively [5.7].

Inadequate awareness and skill towards Driving by Older Drivers:

As per last periodic assessment on awareness state of the driver and requirements in light of safe driving, the transportation authorities decided to assign scores of 10 and 20 out of 100 for cognitive and physical workloads placed on the driver as the result of his/her awareness and skill, respectively (i.e., 0 is most suitable and 100 is least suitable) [5.7]. The participation record of the driver in special training, his/her driving record in terms of traffic ticket and accidents, driving experience as well as the recorded driver's conduct by the in vehicle technologies can all be based on determining the appropriate scores [5.7]. The initial values for IC_{IAD} and IP_{IAD} have been set by auto industries 0.10 and 0.05; respectively [5.7].

Driving under influence:

As per live assessments by in vehicle technologies (e.g., vigilance monitoring system, alcohol detection system) and the self subjective assessment of driver in case of fatigue at a given time (e.g., in minute 45 of driving) on driving under influence state of the driver and requirements in light of safe driving, the total scores of 220 and 180 out of 250 for cognitive and physical workload placed on the driver are assigned; respectively (i.e., 0 is most suitable and 250 is least suitable) [5.7]. The workloads are as the result of his/her driving under influence state. The initial values for IC_{DUI} and IP_{DUI} have been set by auto industries 0.25 and 0.05; respectively [5.7]. It is to be noted that this component of formula can be broken down into various sub-elements depending on the needs, that is, the separate scores, multipliers and limits for each of factors influencing the driving such as alcohol, fatigue and medications can be integrated into the formula [5.7].

Subsequently, the above mentioned values can be substituted into the left side of Eq. (5.3) as follows [5.7]:

$$\begin{aligned}
 & IC_{DUI} \times C_{DUI}(t) + IC_{DRT} \times C_{DRT}(t) + IC_{NMF} \times C_{NMF}(t) + IC_{IAD} \times C_{IAD}(t) + IP_{DUI} \times \\
 & P_{DUI}(t) + IP_{DRT} \times P_{DRT}(t) + IP_{NMF} \times P_{NMF}(t) + IP_{IAD} \times P_{IAD}(t) = 0.25 \times 220 + 0.20 \times \\
 & 110 + 0.20 \times 70 + 0.10 \times 10 + 0.05 \times 180 + 0.05 \times 70 + 0.10 \times 60 + 0.05 \times 20 = \\
 & 55 + 22 + 14 + 1 + 9 + 3.5 + 6 + 1 = 111.5
 \end{aligned}$$

As the above obtained result exceeds the value in the right side of Eq. (5.3) (*i.e.*, $111.5 \gg HC_{DB} = 100$), the system shall trigger a warning message to the driver that his/her further driving is not recommended. The higher the deviation of obtained value from the capacity, the message to driver shall indicate that the more dangerous is going to be further driving until a possible point that vehicle over rides the control from the driver [5.7].

CHAPTER 6

STOCHASTIC RISK ASSESSMENT METHODOLOGY AND MODELING AS IN-VEHICLE SAFETY ENHANCING TOOL FOR YOUNGER DRIVERS ON ROADS

6.1 BACKGROUND

Young novice drivers are expected to outperform in terms of their physical and sensory abilities compared to other age groups in general [6.1]. However, as they lack enough experience in driving and act more emotionally and passionately due to their age, the outcomes of their perception and decision making process can not be in the same quality and soundness as healthy experienced drivers [6.1, 6.2]. These result in higher accident rates among younger drivers [6.3]. Subsequently, these drivers cannot react proactively and appropriately to the events on roads that they had no prior exposure or information concerning it [6.1].

The research has highlighted the growing rate of younger drivers' population as the result of the vital universal need for mobility by everyone and better quality of life. The high risk of driving by young novice drivers is then highlighted. The author has then identified the limitations of younger drivers. The available measures to eliminate or reduce the risks have then been highlighted and modeled logically using Fault Tree Analysis (FTA). Furthermore, the author has gone on highlighting and mathematically modeling the risk of driving by younger drivers at any given time. It has been illustrated how various factors can

interact and have individual and collective time-dependent effects on the safety of driving. A new concept in using the developed risk assessment model in condition monitoring of younger drivers has then been proposed.

6.2 THE FTA OF YOUNGER DRIVERS FAILURE LEADING TO SEVERE CRASH

Transport sector activities focus on ensuring the safe and efficient operation of the road traffic system by encouraging the correct use of the network by road users [6.4]. Traffic is as the result of interactions between people, vehicles and road infrastructure and the human in this process is the key and weakest element [6.5].

Fault tree analysis (FTA) is an excellent risk analysis technique to assess system safety and reliability both qualitatively and quantitatively [6.6, 6.7, 6.8].

The fault tree of younger drivers involved in collisions with severe consequences has been developed and the resulting fault tree is shown in Figure 6.1 [6.9].

6.3 THE STOCHASTIC RISK ASSESSMENT OF YOUNGER DRIVERS ON ROADS

Based on the illustrated model in Figure 6.1, the total risk of crash by younger drivers on roads can be obtained from Eq. (6.1) where each of its components can be derived from Eqs. (6.2)-(6.14) representing the partial risks constituting the total risk [6.9]. There has been an assumption that the causal events illustrated in Figure 6.1 are exclusively independent [6.9]. The general reliability equation has been used in Eqs. (6.1)-(6.14) to indicate that there have been no pre-assumed distributions for each of the events illustrated in fault tree model (Fig.

6.1) [6.9]. However, the potential variety in distribution functions of the events can be seen and integrated into the time dependent instantaneous failure rates of the equations [6.9].

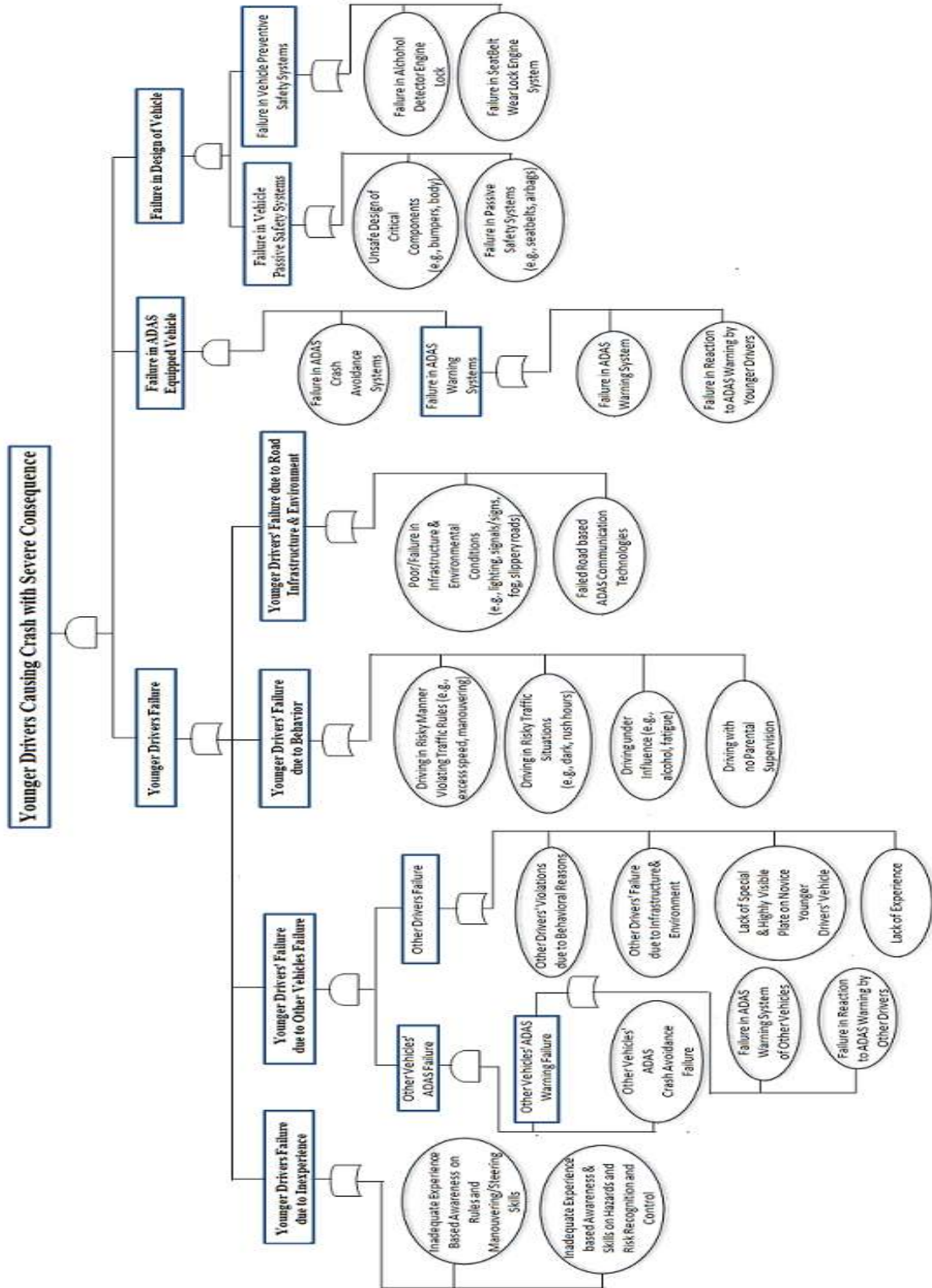


Figure 6.1-FTA of Younger Drivers Causing Crash with Severe Consequence

$$F_{Y-T}(t) = F_{Y-T-F}(t) \times F_{ADAS-T-F}(t) \times F_{DV-T-F}(t) \quad (6.1)$$

$$F_{Y-T-F}(t) = F_{Y-B-F}(t) + F_{Y-RIE-F}(t) + F_{OV-T-F}(t) + F_{Y-IE-F}(t) \quad (6.2)$$

$$F_{Y-B-F}(t) = \left(1 - e^{-\int_0^t \lambda_{Y-B-RVT}(t) dt}\right) + \left(1 - e^{-\int_0^t \lambda_{Y-B-RTS}(t) dt}\right) + \left(1 - e^{-\int_0^t \lambda_{Y-B-UI}(t) dt}\right) \\ + \left(1 - e^{-\int_0^t \lambda_{Y-B-PS}(t) dt}\right) \quad (6.3)$$

$$F_{Y-RIE-F}(t) = \left(1 - e^{-\int_0^t \lambda_{Y-RIE-C}(t) dt}\right) + \left(1 - e^{-\int_0^t \lambda_{Y-RIE-ADAS}(t) dt}\right) \quad (6.4)$$

$$F_{ADAS-T-F}(t) = F_{ADAS-W-F}(t) \times \left(1 - e^{-\int_0^t \lambda_{Y-VADAS-CA}(t) dt}\right) \quad (6.5)$$

$$F_{ADAS-W-F}(t) = \left(1 - e^{-\int_0^t \lambda_{Y-VADAS-WS}(t) dt}\right) + \left(1 - e^{-\int_0^t \lambda_{Y-VADAS-RWS}(t) dt}\right) \quad (6.6)$$

$$F_{DV-T-F}(t) = F_{PS-F}(t) \times F_{VP-F}(t) \quad (6.7)$$

$$F_{PS-F}(t) = \left(1 - e^{-\int_0^t \lambda_{Y-VD-PACC}(t) dt}\right) \times \left(1 - e^{-\int_0^t \lambda_{Y-VD-PASS}(t) dt}\right) \quad (6.8)$$

$$F_{VP-F}(t) = \left(1 - e^{-\int_0^t \lambda_{Y-VD-PRAL}(t) dt}\right) \times \left(1 - e^{-\int_0^t \lambda_{Y-VD-PRSL}(t) dt}\right) \quad (6.9)$$

$$F_{OV-T-F}(t) = F_{OADAS-F}(t) \times F_{OD-F}(t) \quad (6.10)$$

$$F_{OADAS-F}(t) = F_{OADAS-W-F}(t) \times \left(1 - e^{-\int_0^t \lambda_{Y-O-ADAS-CA}(t) dt}\right) \quad (6.11)$$

$$F_{OADAS-W-F}(t) = \left(1 - e^{-\int_0^t \lambda_{Y-O-ADAS-WS}(t) dt}\right) + \left(1 - e^{-\int_0^t \lambda_{Y-O-ADAS-RWS}(t) dt}\right) \quad (6.12)$$

$$F_{OD-F}(t) = \left(1 - e^{-\int_0^t \lambda_{Y-O-VB}(t) dt}\right) + \left(1 - e^{-\int_0^t \lambda_{Y-O-RIE}(t) dt}\right) + \left(1 - e^{-\int_0^t \lambda_{Y-O-LSVP}(t) dt}\right) \\ + \left(1 - e^{-\int_0^t \lambda_{Y-O-IE}(t) dt}\right) \quad (6.13)$$

$$F_{Y-IE-F}(t) = \left(1 - e^{-\int_0^t \lambda_{Y-IE-RM}(t) dt}\right) \times \left(1 - e^{-\int_0^t \lambda_{Y-IE-ASHR}(t) dt}\right) \quad (6.14)$$

The instantaneous failure rate of the driver can best be assumed to follow a bathtub distribution curve (e.g., Fig. 6.2) [6.10]. The bathtub curve (Fig. 6.2) is typically used to

show the characteristics of mechanical components over three periods (i.e., burning or infant mortality, useful life and wear out) [6.10, 6.11, 6.12, 6.13, 6.14].

As Hojjati-Emami [6.10] stated the bathtub curve is expected to move higher for less skilled drivers (i.e., younger drivers) and in the contrary to move lower for more skilled drivers (Fig. 6.2).

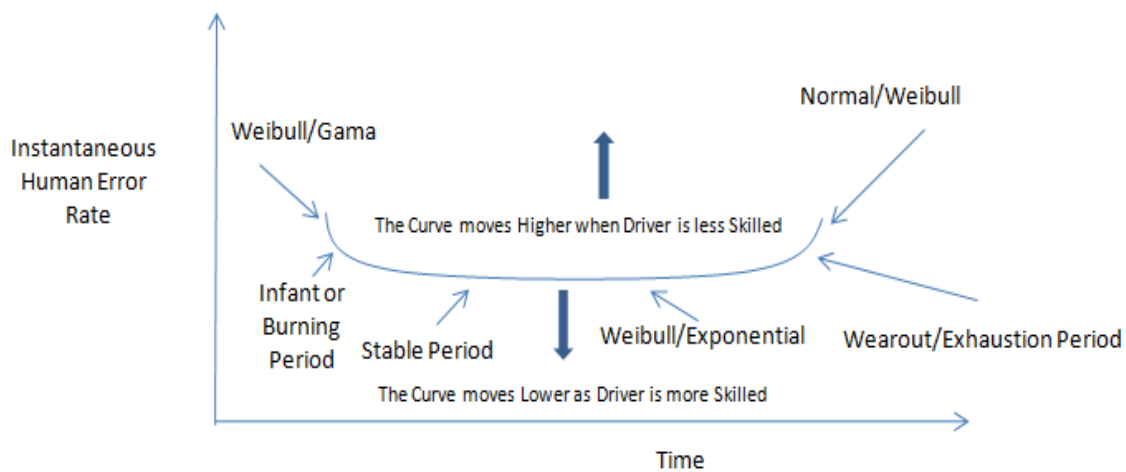


Figure 6.2 – Expected Characteristic of Human Error Rate in Driving Operation

As it is shown in left part of Figure 6.2, it is expected that the instantaneous failure or human error rate of every novice younger driver starts from a rather high value and goes down as they get more experienced [6.9]. This decrease in failure/human error rate continues till a certain point of time that this rate remains stable or fixed over the course of a longer period of time (i.e., second section of the curve in Figure 6.2) [6.9]. However, if the younger drivers drive under risky situations (e.g., peer influence, alcohol, fatigue, dense traffic, poor road conditions), the instantaneous failure/human error rate is expected to accelerate (i.e., the third section of the curve in Figure 6.2) [6.9].

As the younger drivers gain noticeable experience in maneuvering and hazard recognition skills, the curve would be expected to move lower further [6.9].

The estimated failure or human error rate for younger drivers is suggested to be obtained through actual data or experiments or specially designed virtual reality simulators [6.9].

With respect to instantaneous failure rates of physical components affecting the safety of younger drivers on roads as illustrated in the fault tree (i.e., Figure 6.1), it should be mentioned that the appropriate distributions shall be obtained through collected data from accelerated life testing methods or historical real life of systems or available databases and prediction models (e.g., MIL-HDBK-217) [6.9].

6.4 RISK MONITORING OF YOUNGER DRIVERS ON ROADS

The methodology of predicting the risk for younger drivers, as developed and presented in previous section, cannot only be used for assessing and improving the younger drivers' safety related policies and programs but also be utilized to monitor the state of risk for younger drivers right on spot and at any given time [6.9].

By now, there has been no available ADAS technology to fully guarantee the reliable and effective recognition of all types of hazards as they do not guarantee that the safest preventive measures are taken [6.9]. It is certain that a vehicle equipped with ADAS technologies can better safeguard the younger drivers and other motorists on the roads compared to vehicles that lack ADAS technologies or possess less advanced or complete ones [6.9].

The transportation industries and authorities aim continuously to come up with better ADAS technologies in terms of reliability, effectiveness, and applicability [6.9].

Monitoring the risk of driving by younger driver on the roads at any given time using the developed stochastic models (Eqs. 6.1-6.14) and presenting the calculated total risk to the driver through a display is to be seen essential and more critical than much of the information shown to the driver [6.9].

The total risk shall be calculated by a central processor integrated in vehicle based on data collected from in-vehicle and on road technologies as well as direct input from drivers [6.9]. The calculated risk value is suggested to be displayed in a qualitative scale similar to fuel gauge [6.9]. The background of riskometer, the term used for the gauge and a pointer, can be graded to three parts safe mode (over green color background), caution mode (over amber color background) and danger mode (over the red color background) [6.9]. As the risk level goes to caution mode, the intermittent audio and visual warnings will be given to the driver and when it gets to danger mode, the constant audio and visual warnings shall be given [6.15, 6.16].

For highly risky drivers with poor driving background, the information of riskometer can automatically be linked to a black-box system to record all its data over the course of driving for subsequent law enforcement [6.9].

6.5 ILLUSTRATIVE EXAMPLE

It is illustrated in this section how the models (Eqs. 6.1-6.14) can be applied for a younger driver with following hypothetical instantaneous failure rates to assess the risk state at a given time (e.g., $t=100$ min) [6.9]. For simplicity of calculations, it is assumed that all the

instantaneous failure rates are constant and these values are based on failures per minute [6.9]:

$$\begin{aligned}
\lambda_{Y-IE-RM} &= 0.0002 & \lambda_{Y-IE-ASHR} &= 0.0001 & \lambda_{Y-O-ADAS-CA} &= 0.0003 \\
\lambda_{Y-O-ADAS-WS} &= 0.0003 & \lambda_{Y-O-ADAS-RWS} &= 0.0004 & \lambda_{Y-O-VB} &= 0.0007 \\
\lambda_{Y-O-RIE} &= 0.0004 & \lambda_{Y-O-LSVP} &= 0.0006 & \lambda_{Y-O-IE} &= 0.0006 \\
\lambda_{Y-B-RVT} &= 0.0008 & \lambda_{Y-B-RTS} &= 0.0009 & \lambda_{Y-B-UI} &= 0.0004 \\
\lambda_{Y-B-PS} &= 0.0003 & \lambda_{Y-RIE-C} &= 0.0008 & \lambda_{Y-RIE-ADAS} &= 0.0008 \\
\lambda_{Y-VADAS-CA} &= 0.0004 & \lambda_{Y-VADAS-WS} &= 0.0007 & \lambda_{Y-VADAS-RWS} &= 0.0002 \\
\lambda_{Y-VD-PACC} &= 0.0006 & \lambda_{Y-VD-PASS} &= 0.0009 & \lambda_{Y-VD-PRAL} &= 0.0005 \\
\lambda_{Y-VD-PRSL} &= 0.0005 & & & &
\end{aligned}$$

The younger driver in this example is considered to be in typically accepted age group of younger drivers (e.g., 18-24 yrs old) with his/her own unique behavioral characteristics and with specific driving awareness and record [6.9]. Thus, substitutions the given values into Equations (6.1)-(6.14), we obtained [6.9]:

$$F_{Y-T}(t) = F_{Y-T-F}(t) \times F_{ADAS-T-F}(t) \times F_{DV-T-F}(t) = 1.468 \times 10^{-8} \quad (6.15)$$

$$F_{Y-T-F}(t) = F_{Y-B-F}(t) + F_{Y-RIE-F}(t) + F_{OV-T-F}(t) + F_{Y-IE-F}(t) = 0.360698 \quad (6.16)$$

$$\begin{aligned}
F_{Y-B-F}(t) &= \left(1 - e^{-\int_0^t \lambda_{Y-B-RVT}(t) dt}\right) + \left(1 - e^{-\int_0^t \lambda_{Y-B-RTS}(t) dt}\right) + \left(1 - e^{-\int_0^t \lambda_{Y-B-UI}(t) dt}\right) \\
&\quad + \left(1 - e^{-\int_0^t \lambda_{Y-B-PS}(t) dt}\right) = 0.206282 \quad (6.17)
\end{aligned}$$

$$F_{Y-RIE-F}(t) = \left(1 - e^{-\int_0^t \lambda_{Y-RIE-C}(t) dt}\right) + \left(1 - e^{-\int_0^t \lambda_{Y-RIE-ADAS}(t) dt}\right) = 0.153766 \quad (6.18)$$

$$F_{ADAS-T-F}(t) = F_{ADAS-W-F}(t) \times \left(1 - e^{-\int_0^t \lambda_{Y-VADAS-CA}(t) dt}\right) = 0.00342 \quad (6.19)$$

$$F_{ADAS-W-F}(t) = \left(1 - e^{-\int_0^t \lambda_{Y-VADAS-WS}(t) dt}\right) + \left(1 - e^{-\int_0^t \lambda_{Y-VADAS-RWS}(t) dt}\right) = 0.0874 \quad (6.20)$$

$$F_{DV-T-F}(t) = F_{PS-F}(t) \times F_{VP-F}(t) = 0.000012 \quad (6.21)$$

$$F_{PS-F}(t) = \left(1 - e^{-\int_0^t \lambda_{Y-VD-PACC}(t) dt}\right) \times \left(1 - e^{-\int_0^t \lambda_{Y-VD-PASS}(t) dt}\right) = 0.005011 \quad (6.22)$$

$$F_{VP-F}(t) = \left(1 - e^{-\int_0^t \lambda_{Y-VD-PRAL}(t) dt}\right) \times \left(1 - e^{-\int_0^t \lambda_{Y-VD-PRSL}(t) dt}\right) = 0.002378 \quad (6.23)$$

$$F_{OV-T-F}(t) = F_{OADAS-F}(t) \times F_{OD-F}(t) = 0.000453 \quad (6.24)$$

$$F_{OADAS-F}(t) = F_{OADAS-W-F}(t) \times \left(1 - e^{-\int_0^t \lambda_{Y-O-ADAS-CA}(t) dt}\right) = 0.00203 \quad (6.25)$$

$$F_{OADAS-W-F}(t) = \left(1 - e^{-\int_0^t \lambda_{Y-O-ADAS-WS}(t) dt}\right) + \left(1 - e^{-\int_0^t \lambda_{Y-O-ADAS-RWS}(t) dt}\right) = 0.06876 \quad (6.26)$$

$$F_{OD-F}(t) = \left(1 - e^{-\int_0^t \lambda_{Y-O-VB}(t) dt}\right) + \left(1 - e^{-\int_0^t \lambda_{Y-O-RIE}(t) dt}\right) + \left(1 - e^{-\int_0^t \lambda_{Y-O-LSVP}(t) dt}\right) + \left(1 - e^{-\int_0^t \lambda_{Y-O-IE}(t) dt}\right) = 0.22326 \quad (6.27)$$

$$F_{Y-IE-F}(t) = \left(1 - e^{-\int_0^t \lambda_{Y-IE-RM}(t) dt}\right) \times \left(1 - e^{-\int_0^t \lambda_{Y-IE-ASHR}(t) dt}\right) = 0.000197 \quad (6.28)$$

The calculated value for Equation (6.15) (i.e., 1.468×10^{-8}) represents the total risk of crash by the younger driver at the given time (i.e., $t=100\text{min}$) where the ADAS is assumed to be fully complete and to warn and prevent all types of failures by the driver [6.9]. Under circumstances that the vehicle is equipped with less complete ADAS system or lacks ADAS

system, the ADAS just in those areas being effective and operational should be taken into account in the analyses and calculations and thus the risk is expected to be higher [6.9].

CHAPTER 7

THE HRA-BASED ROAD CRASH DATA: A METHODOLOGY FOR CRASH INVESTIGATION AND VALIDATING THE DISTRIBUTION CHARACTERISTICS OF DRIVER'S FAILURE RATE

7.1 BACKGROUND

The significance of human reliability data for road transportation and the types of data needed for a systematic human reliability assessment in a car crash caused by a driver have been highlighted and presented in this research. The research also presents a thorough procedure for road accident investigation and the data collection. Then, the research stresses on the need for development of effective databanks on road transportation safety and examines the requirements of such database and then develops and presents a concept for such database.

Furthermore, the validity of the proposed distribution characteristics form for drivers' instantaneous failure rate on roads has been tested experimentally to pave the way for more accurate data collection and processing as part of risk assessments. The findings of this research would assist the road safety researchers and authorities in their investigation and assessment processes and subsequently would be used to enhance the safety of roads with taking more suited proactive measures using right data and assessments.

7.2 THE DRIVERS' FAILURE DATA IN ROAD ACCIDENTS WITH PROPOSED INVESTIGATION PROCEDURE AND FRAMEWORK FOR HRA ROAD DATABANKS

The road crash data (e.g., crash location, road conditions/environments, vehicles involved, drivers, passengers, casualties, and mainly immediate factors contributed in crash) are everyday being collected, recorded and stored by Police and Transportation Authorities in their databases across the Globe (e.g., [7.1, 7.2, 7.3, 7.4, 7.5, 7.6]).

However, these data at best scenario can include the above-mentioned information which does not suffice the needs for a thorough human reliability assessment in order to identify the latent and active or immediate causes of accidents and subsequently to seek appropriate remedial or proactive measures [7.7, 7.8]. It appears that these data and information being collected and processed are more applicable for use by analysts in insurance, law enforcement, healthcare, economics domains and not for well rooted and systematic analyses by transportation authorities in elimination or reduction of the accidents risks [7.7, 7.8].

7.2.1 THE INVESTIGATION PROCEDURE AND DATA COLLECTION FOR ROAD ACCIDENTS

Due to the above described issues with available road crash databases, the author has proposed that the best methodology for conducting HRA-based investigation and collecting the necessary data in road crashes is to use the developed accident investigation procedure as illustrated in Figure 7.1 [7.7, 7.8]. The proposed investigation procedure (Fig. 7.1) has

been developed and extracted from an integrative fault tree model as illustrated in Figure 7.2 derived from the earlier works of the author [7.7, 7.8, 7.9, 7.10, 7.11].

The form illustrated in Figure 7.3 is the author's developed concept for investigation and collection of accident data by police authorities and representatives of transportation authorities following a car involved accident [7.8]. The principle data used in the proposed form are derived from the works presented in Figures 7.1 and 7.2 [7.7, 7.8]. The data to be collected in the form can be sought through various channels including interviews with drivers, passengers, witnesses, data recorders in the vehicles or on roads, expert opinions of law enforcement officers, etc. [7.8].

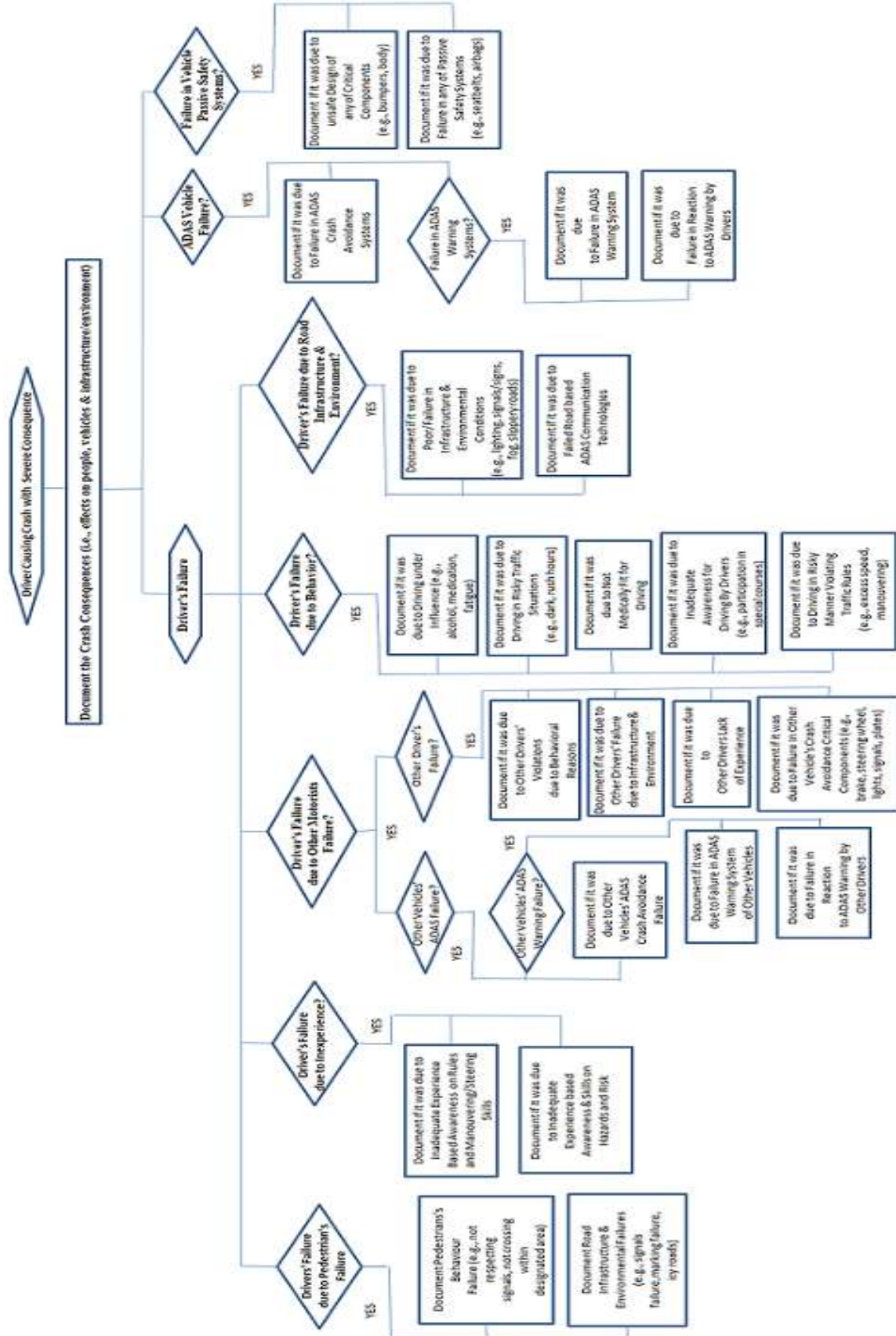


Figure 7.1. HRA Based Investigation Procedure of Driver Caused Crash with Severe Consequence

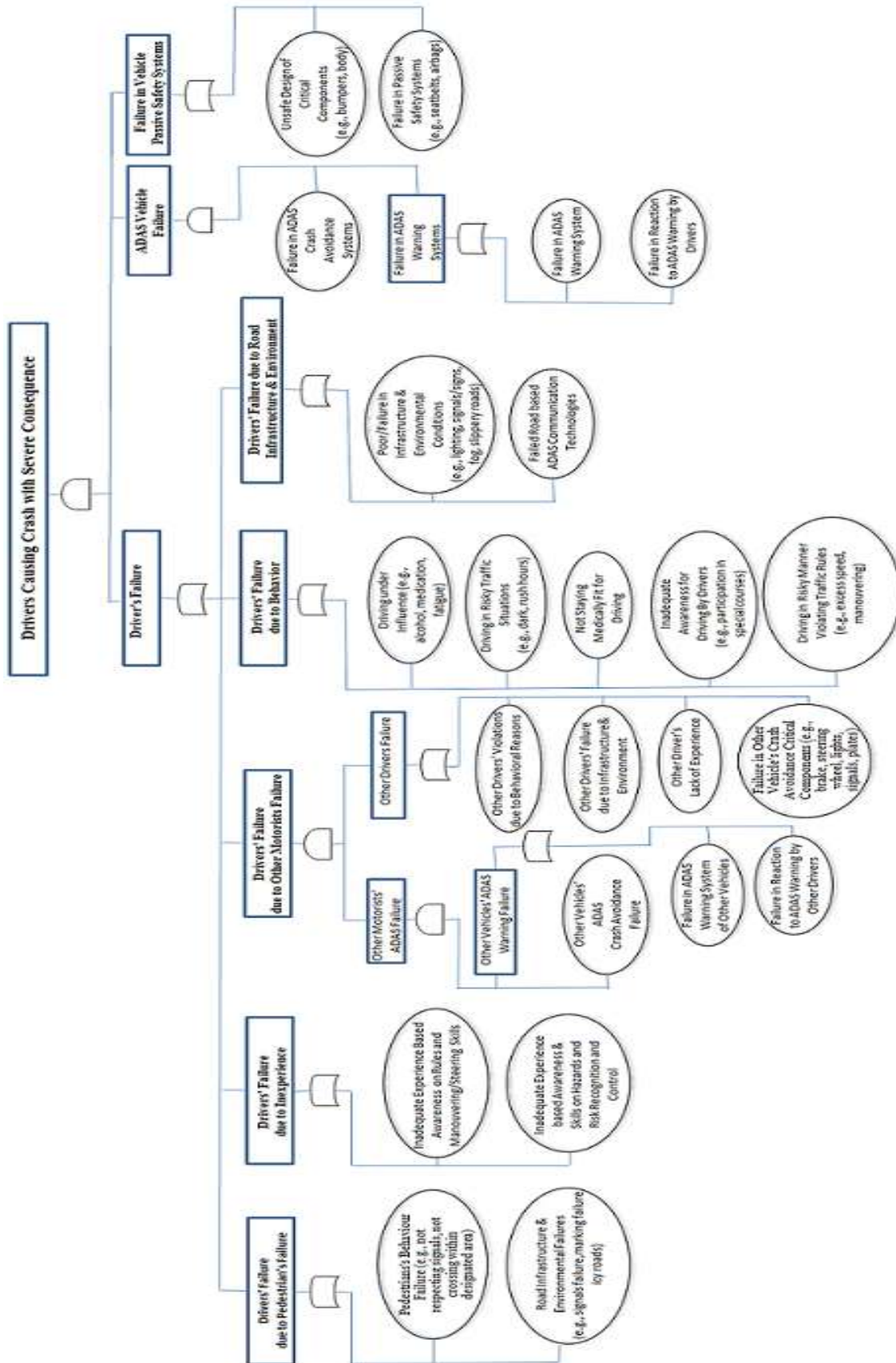


Figure 7.2: FTA of Drivers Causing Crash with Severe Consequence

HRA-Based Road Accident Investigation Form

Investigation Analyst(s):

Signature(s):

Date:

Affiliations/Contact Info:

The Driver(s) Causing Crash with Severe Consequence:

Age(s): Sex: Vehicle(s): Plate #: Date: Location:
 Drivers License #: Time of Crash: Time the Trip Began: Time from the Last Stop for Fatigue Recovery:

Crash Consequences:
 Effects on Driver(s): Effects on Vehicles:
 Effects on Passengers: Effects on Environment/Road Infrastructure:

A. Failures in Vehicle Passive Safety System?
 1-Was it due to unsafe Design or Failure in any of Critical Components (e.g., bumpers, body, Brakes, Steering Wheel)? If any, Document Your Assessment:
 2-Was it due to Failure in any of Passive Safety Systems (e.g., seatbelts, airbags)? If any, Document Your Assessment:

B. Failures in Vehicle's ADAS:
 1-Was it due to Failure in ADAS Crash Avoidance Systems? If any, Document Your Assessment:
 2-Was it due to Failure in ADAS Warning System? If any, Document Your Assessment:
 3-Was due to Failure in Reaction to ADAS Warning by Drivers? If any, Document Your Assessments:

C. Driver's Failure due to Road Infrastructure & Environment:
 1-Was it due to Poor/Failure in Infrastructure & Environmental Conditions (e.g., lighting, signals/signs, fog, slippery roads)? If any, Document Your Assessment:
 2-Was it due to Failed Road based ADAS Communication Technologies? If any, Document Your Assessment:

D. Driver's Failure due to Behavior:
 1-Was it due to Driving under Influence (e.g., alcohol, medication, fatigue)? If any, Document Your Assessment:
 2-Was it due to Driving in Risky Traffic Situations (e.g., dark, rush hours)? If any, Document Your Assessments:
 3-Was it due to Medical Condition? If any, Document Your Assessments:
 4-Was it due to Inadequate Awareness and Care for Safe Driving (e.g., participation in special courses)? If any, Document Your Assessments:
 5-Was it due to Driving in Risky Manner Violating Traffic Rules (e.g., excess speed, manoeuvring)? If any, Document Your Assessments:

E. Driver's Failure due to Inexperience:
 1-Was it due to Inadequate Experience Based Awareness on Rules and Manoeuvring/Steering Skills? If any, Document Your Assessments:
 2-Was it due to Inadequate Experience based Awareness & Skills on Hazards and Risk Recognition and Control? If any, Document Your Assessments:

F. Driver's Failure due to Other Motorists Failure:
 1-Was it due to Other Drivers' Violations due to Behavioral Reasons? If any, Document Your Assessments:
 2-Was it due to Other Drivers' Failure due to Infrastructure & Environment? If any, Document Your Assessments:
 3-Was it due to Other Drivers Lack of Experience? If any, Document Your Assessments:
 4-Was it due to Other Vehicle's Crash Avoidance Critical Components (e.g., brake, steering wheel, lights, signals, plates)? If any, Document Your Assessments:
 5-Was it due to Other Vehicles' ADAS Crash Avoidance Failure? If any, Document Your Assessments:
 6-Was it due to Failure in ADAS Warning System of Other Vehicles? If any, Document Your Assessments:
 7-Was it due to Failure in Reaction to ADAS Warning by Other Drivers? If any, Document Your Assessments:

G. Drivers' Failure due to Pedestrian's Failure:
 1-Was it due to Pedestrians's Behaviour Failure (e.g., not respecting signals, not crossing within designated area)? If any, Document Your Assessments:
 2-Was the Pedestrian's Failure due to Road Infrastructure & Environmental Failures (e.g., signals failure, marking failure, icy roads)? If any, Document Your Assessments:

Use As Many Extra Sheets As Necessary in Support of Your Assessment on Each Section and Question Citing the Code of Specific Question (e.g., G1 (PAGE#.../...))

Figure 7.3-HRA-Based Road Accident Investigation & Data Collection Form

7.2.2 THE REQUIREMENTS AND PROPOSED MODEL FOR HRA DATA-BANKS IN ROAD TRANSPORTATION

As it was stated previously, the data available in general Human Reliability Databases are not usable for road transportation safety analyses as the data are neither related to road transportation nor they are processed in a manner required for typical human reliability assessments for road transportation systems [7.7, 7.8]. The road related data that are currently being collected and processed by the authorities in many countries and regions are limited and related to recognition of immediate causes of accidents, their consequences/effects and the conditions immediately surrounding the accident, and not their root or latent causes (e.g., [7.2, 7.7, 7.8, 7.9, 7.10, 7.11, 7.12, 7.13]). These data are also not tabulated and processed for the benefit of quantitative and qualitative human reliability assessments in a systematic manner. Thus, the complete benefit of these collected data cannot currently be attained [7.7].

To make road transportation data for human reliability assessment useful, they should be collected and processed by transportation authorities according to the developed Fault Tree Analysis (FTA) chart as shown in Figure 7.1 [7.7, 7.8, 7.9, 7.10, 7.11, 7.12, 7.13]. Figure 7.1 illustrates logically all the root causes and their dependencies for a severe accident caused by the driver. The author has converted the developed FTA (Fig. 7.1) into a proposed accident investigation procedure for collection of necessary human reliability related data as presented in Figure 7.2 [7.7, 7.8]. The developed procedure and the subsequent data collection form shown in Figures 7.2 and 7.3 could be used by the crash

investigators as a guideline to collect data necessary for human reliability assessments [7.7, 7.8].

There is a need for various road reliability data to be collected. Some data are qualitative concerning vehicle-road-driver-passenger system, causes of accidents and modes of failures using the investigation procedure and data collection form developed and presented in Figures 7.2 and 7.3 [7.7, 7.8]. Other kind of data including the time to failure which is in quantitative form (i.e., from moment zero of the trip to time of accident) for each failure mode shall be obtained subjectively and objectively in order to fit the right distribution for failure rate per each mode of failure [7.7, 7.8].

As it has been suggested by the author [7.9], the failure rates for the experienced drivers (whether adult or older drivers) and younger drivers groups (containing a distinct learning phase) are expected to follow such distributions as previously illustrated in Figures 2.2 and 6.2; respectively. Figure 2.2 illustrates that the instantaneous failure rates of experienced drivers in a single trip should remain constant [7.7, 7.8, 7.9]. However, as he/she reaches exhaustion point the failure rate can increase [7.7, 7.8]. The more experienced the driver becomes, the less failure rate will be expected and vice versa. Figure 6.2 illustrates that the instantaneous failure rates of younger drivers in a single trip may vary if he/she is in his initial learning period (i.e., the first part of curve), remain constant (i.e., second part of curve when the infant/burning period of bathtub distribution passes) and increase (i.e., third part of curve when he/she reaches exhaustion point) [7.7, 7.8, 7.9]. The more experienced the driver becomes, the less failure rate will be expected during trips and vice versa [7.7, 7.8, 7.9].

It is suggested that the data for time to accident should be collected and processed separately for various groups of drivers including younger drivers, older drivers, and experienced drivers [7.8]. Mixing the data related to these three groups can skew the shape and parameters of the failure rate distribution and could lead to the wrong interpretation and use of data in the process of mitigating the risks [7.8].

Furthermore, it is recommended that transportation authorities in various countries and regions should continually collect data and re-draw these distribution curves to monitor the results of mitigation and remedial action efforts taken for the betterment of drivers' safety subsequent to the investigation process. It is to be noted that not only between but within each age group (i.e., younger drivers, experienced drivers and older drivers), there are going to be differences in terms of failure rates.

In human factors discipline, the percentile concept is used in assessment and design analyses whether for physical or cognitive characteristics of human. Similarly, this concept shall be used when the collected human failure data is going to be processed and presented in databases.

It is also suggested that the modern databanks in road transportation should contain a description of mitigation and follow up actions taken for each individual failure mode identified in the accident investigation process so that the efficacy of mitigation efforts can be evaluated and documented over time.

The road transportation sector needs reliability data to understand and identify the issues in any specific road transportation system composed of driver, road, environment and vehicles and then to improve the reliability of system and monitor the situation over the time. By reliability data, we mean information about failure/error modes, time to failure

distributions, failure rates, and corrective measures for any of the above noted components of road transportation system [7.14].

However, we should note that human is heavily the key and ultimate source in control of the vehicle up to last moment prior to accident even though the causes may be rooted in non human related factors as described in previous sections.

The focus of data collection in the road accidents is to be based on human centered reliability assessment as Figures 2.2, 6.2, and 7.1-7.3 all indicate. Subsequently, the collected data should be fed to such a database format as proposed in Figure 7.4 for ease of data maintenance, processing, monitoring, and improving or correcting the situation.

Human Centered Reliability Data-Bank for Accidents in Road Transportation									
Street/Road/Highway Name:	Street/Road/Highway/Traffic Specifications:			Time Period of Coverage: Data Collected from Date of _____ to _____ for <input type="radio"/> All Seasons <input type="radio"/> Spring <input type="radio"/> Summer <input type="radio"/> Fall <input type="radio"/> Winter during _____ hrs to _____ hrs			Page: _____/_____		
District/City/Province/Country:	Total Drivers Population in the Survey: <input type="radio"/> Younger Drivers Population: <input type="radio"/> Experienced Drivers Population: <input type="radio"/> Older Drivers Population:			Total Aggregated Driving Time (hrs) in the Survey: <input type="radio"/> Aggregated Younger Drivers' Driving Time: <input type="radio"/> Aggregated Experienced Drivers' Driving Time: <input type="radio"/> Aggregated Older Drivers' Driving Time:			Remarks:		
Failure Mode	No. of Human Failures Causing Severe Consequence (Col.2)	Failure Rate (FR) (Col.2/Col.3)	FR Mean	Standard Deviation (SD)	%Selected Percentile Value of FR=Z*(Standard Deviation)/(SD)/FR Mean	Proposed Corrective Action(s)	Corrective Action(s) Implemented	Date of Corrective Action(s) Implemented	
<p>A. Failures in Vehicle's Critical Components or Passive Safety Systems:</p> <p>A.1. Unsafe Design or Failure in any of Critical Components of Vehicle (e.g., bumpers, body, Brakes, Steering Wheel)</p> <p>A.2. Failure in any of Passive Safety Systems (e.g., seatbelts, airbags)</p> <p>B. Failures in Vehicle's ADAS:</p> <p>B.1. Failure in ADAS Crash Avoidance Systems</p> <p>B.2. Failure in ADAS Warning System</p> <p>B.3. Failure in Reaction to ADAS Warning by Drivers</p> <p>C. Driver's Failure due to Road</p>									

Figure 7.4-A Proposed Human-Centered-Reliability DataBank for Accidents in Road Transportation

C. Driver's failure due to Road Infrastructure & Environment:
 C.1. Poor/Failure in Infrastructure & Environmental Conditions (e.g., lighting, signs/signs, fog, slippery roads)
 C.2. Failure in Road based ADAS Communication Technologies

D. Driver's failure due to Behavior:
 D.1. Driving under influence (e.g., alcohol, medication, fatigue)
 D.2. Driving in Risky Traffic Situations (e.g., overtaking, non hours)
 D.3. Medical Condition
 D.4. Inadequate Awareness and Care for Safe Driving (e.g., participation in special courses)
 D.5. Driving in Risky Manner Violating Traffic Rules (e.g., excess speed, manoeuvring)

E. Driver's failure due to Inexperience



Figure 7.4-A Proposed Human-Centered-Reliability DataBank for Accidents in Road Transportation (Continued)

7.3 THE CHARACTERISTICS OF DRIVERS' INSTANTANEOUS FAILURE RATE

This data is one of key data to be collected using the proposed investigation form (Fig. 7.3). It has been proposed that the expected distributions of instantaneous failure rates for the younger drivers and experienced drivers (whether adult or older drivers) follow the distributions illustrated in Figures 2.2 and 6.2; respectively [7.8, 7.11, 7.13].

7.3.1 THE REQUIREMENTS AND CONCEPT OF HAZARD PLOTTING METHOD FOR TESTING THE INSTANTANEOUS FAILURE RATE OF DRIVERS

The hazard function, cumulative distribution function, and the cumulative hazard function are mathematically defined by Equations (7.1)-(7.3); respectively [7.8].

$$Z(t) = \frac{f(t)}{R(t) - f(t)} \quad (7.1)$$

$$F(t) = \int_0^t f(t) dt \quad (7.2)$$

$$Z_c(t) = \int_0^t Z(t) dt \quad (7.3)$$

Both Figures 2.2 and 6.2 suggest that the hazard or instantaneous failure rates for drivers remain constant for a stable period of driving task by a driver until their exhaustion points in any given trip [7.8].

Using Equations (7.1)-(7.3), the hazard (instantaneous) failure rate and cumulative hazard rate for the stable period of driving task can be obtained from Equations (7.4) and (7.5) [7.8].

$$Z(t) = \lambda t \quad (7.4)$$

$$Z_c(t) = \lambda t^2 \quad (7.5)$$

By letting $\lambda = \frac{1}{\alpha}$, where α is the mean time to failure and rearranging Equation (7.5) to express the time to failure, t , as a function of Z_c , we get [7.8]:

$$t = \alpha Z_c(t) \quad (7.6)$$

Equation (7.6) is the equation of a straight line passing through the origin. In order to estimate the value of α , the time to failure t against the cumulative hazard Z_c is plotted. If the plotted field data points fall roughly on a straight line, then the distribution is exponential and the value of α equals the slope of the straight line [7.8].

Furthermore, Figures 2.2 and 6.2 suggest that the hazard or instantaneous failure rates for a driver increases weibully when the driving task continues beyond exhaustion point. Using Equations (7.1)-(7.3), the hazard or instantaneous failure rate and the cumulative hazard rate for Weibull distribution can be obtained from Equations (7.7) and (7.8) [7.8].

$$Z(t) = \frac{\theta}{\beta^\theta} t^{\theta-1} \quad (7.7)$$

$$Z_c(t) = \left(\frac{t}{\beta}\right)^\theta \quad (7.8)$$

By rearranging Equation (7.8) to express the time to failure, t , as a function of Z_c , we get [7.8]:

$$\ln t = \frac{1}{\theta} \ln Z_c + \ln \beta \quad (7.9)$$

Equation (7.9) is the equation of a straight line passing through the origin. When the plotted data points approximately fall along a straight line, this indicates that the failure data belongs to a Weibull distribution [7.8].

7.3.2 EXPERIMENTAL VALIDATION OF CHARACTERISTICS FOR DRIVER'S INSTANTANEOUS FAILURE RATE

An experiment was designed to test the validity of presumed constant characteristics of driver's instantaneous failure rate (Figures 2.2 & 6.2) from the start of a trip to the moment that driver reaches his/her exhaustion point [7.8]. The route selected for this experiment was Haraz road linking Tehran to Babolsar in the shore of Caspian Sea with total distance of 250 km in either direction or the average driving duration of four hours depending on traffic and environmental condition (Fig. 7.5) [7.8].



Figure 7.5-Tehran-Babolsar via Haraz Road : the 1st Experiment Location

The test was conducted on a sole experienced driver, the author, with 30 years of North American and local driving experience with no records of accident but with experience of a number of near-miss accidents [7.8]. The test was conducted 25 times, that is, 25 experimental trips each totaling 250km distance [7.8]. The road is considered as a very demanding and potentially hazardous road due to its mountainous condition of road and traffic. The vehicle used for the test had no ADAS system. The driver's failures with potential of causing accidents or near miss accidents were determined to include any risky and hazardous lane departures, passing other vehicles, sudden brake due to unsafe distance from vehicle ahead, fast turning, etc. [7.8]. The vehicle was equipped with voice recorder and a large stop-watch placed on top of dashboard. The driver was instructed to start stop-watch and voice recorder at the beginning of his trip and records the time and type of near miss accidents once he confronts with one of the above listed failures [7.8]. Furthermore, the driver was asked to stop driving as soon as he feels that he has reached the fatigue level whether mentally or physically that can be degrading his performance [7.8]. The Table 7.1

presents failure and running times of the 25 identical tests as well as calculated data as per steps required in a hazard plotting method (Eqs. 7.1-7.6) [7.8].

Table 7.1 - Hazard Plot Data for Validating Exponential Distribution Assumption of Time to Failure

Data No.	Data No. in Descending Order	Failure & Running/ Censoring Times (min.)	Times in Ascending Order (min.)	Hazard (%)	Cumulative Hazard (%)
		*Running/Censoring time			
1	25	240*	66	1/25=0.04	0.04
2	24	160	77	1/24=0.042	0.082
3	23	85	85	1/23=0.043	0.125
4	22	240*	98	1/22=0.045	0.17
5	21	98	102	1/21=0.048	0.218
6	20	240*	110	1/20=0.05	0.268
7	19	240*	125	1/19=0.053	0.321
8	18	240*	145	1/18=0.055	0.376
9	17	125	155	1/17=0.059	0.435
10	16	214	160	1/16=0.063	0.498
11	15	66	175	1/15=0.067	0.565
12	14	240*	198	1/14=0.071	0.636
13	13	155	210	1/13=0.077	0.713
14	12	198	214	1/12=0.083	0.796
15	11	210	240*	1/11=0.091	---
16	10	110	240*	1/10=0.1	---
17	9	240*	240*	1/9=0.111	---
18	8	77	240*	1/8=0.125	---
19	7	240*	240*	1/7=0.143	---
20	6	145	240*	1/6=0.167	---
21	5	167	240*	1/5=0.2	---
22	4	240*	240*	1/4=0.25	---
23	3	240*	240*	1/3=0.333	---
24	2	240*	240*	1/2=0.5	---
25	1	102	240*	1/1=1	---

The plotted data (Figure 7.6) indicates that the times to failure can closely be fitted to a straight line [7.8]. Therefore, the assumption of exponential distribution for time to failure and subsequently the constant value for instantaneous failure rate are considered valid [7.8].

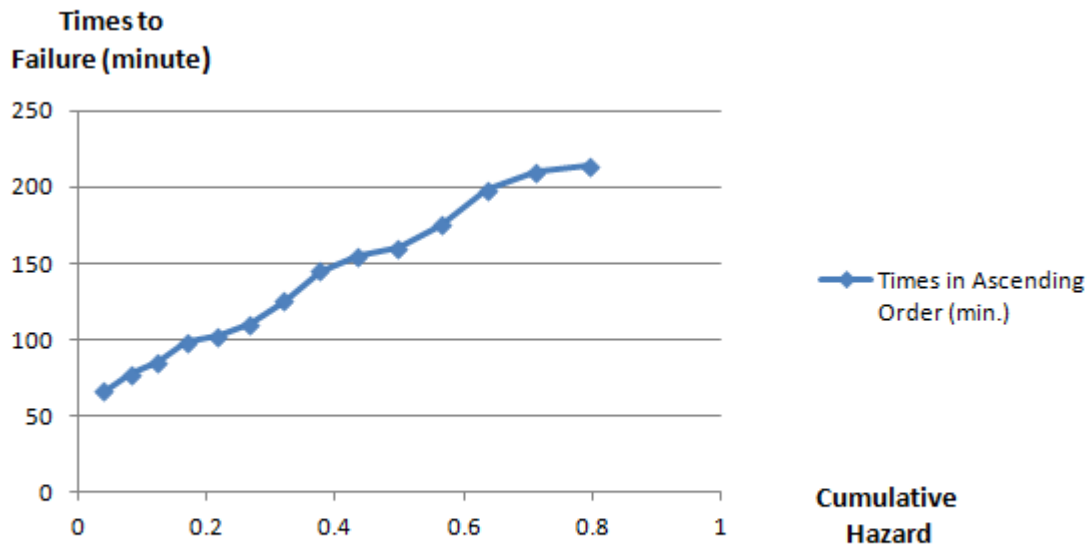


Figure 7.6-Failure Data Fit to an Exponential Distribution

Similarly, the author conducted seven additional tests on the same driver in another route (i.e., from Tehran to Babolsar via Challoos road) (Figure 7.7) with longer distance to determine the distribution characteristics of time to failure beyond exhaustion point of driver [7.8]. The selected route was 320 km distance and due to the heavy traffic and mountaneous road, it took 8 hrs of driving on average in either direction. The driver was instructed to drive beyond exhaustion point until he commits one of those hazardous failures as identified in previous experiment and then to record orally the time of failure reading from stopwatch [7.8].



Figure 7.7-T ehran-Babolsar via Chaloos Road: the 2nd Experiment Location

The Table 7.2 contains the data collected from the tests and the required calculations as per hazard plot technique (Eqs. 7.1-7.3 & Eqs. 7.7-7.9) [7.8].

Table 7.2 - Hazard Plot Data for Validating Distribution of Driver's Failure beyond Driver's Exhaustion Point

Data No.	Data No. in Descending Order	Failure & Running/ Censoring Times (min.)	Times in Ascending Order (min.)	Hazard (%)	Cumulative Hazard (%)	ln (Time to Failure)	ln (Cumulative Hazard)
		*Running/Censoring time					
1	7	372	148	$1/7=0.143$	0.143	5	2.66
2	6	420*	194	$1/6=0.166$	0.309	5.26	3.43
3	5	269	269	$1/5=0.2$	0.509	5.59	3.93
4	4	420*	372	$1/4=0.25$	0.759	5.91	4.33
5	3	186	390	$1/3=0.333$	1.092	5.97	4.69
6	2	390	420	N/A	N/A	N/A	N/A
7	1	194	420	N/A	N/A	N/A	N/A

The plotted data (Figure 7.8) indicates that the times to failure beyond driver's exhaustion point can approximately be fitted to a straight line [7.8]. Therefore, the assumption of Weibull distribution for time to failure beyond exhaustion point and subsequently the increasing value for instantaneous failure rate are considered true [7.8].

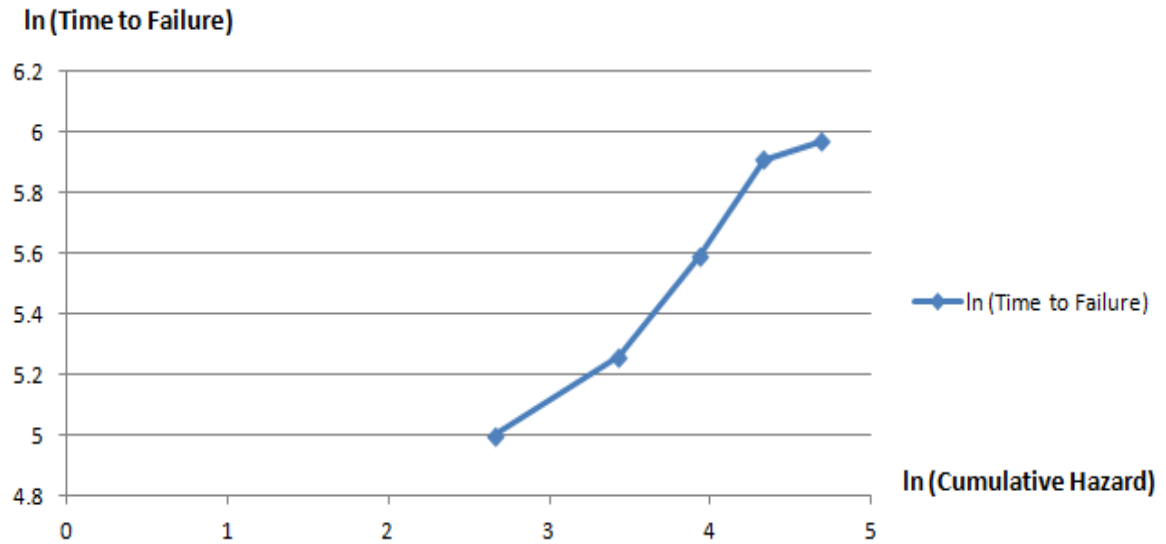


Figure 7.8-Failure Data Fit to a Weibull Distribution

CHAPTER 8

DISCUSSIONS, CONCLUSION AND FUTURE DIRECTIONS

8.1 IDENTIFICATION AND INTEGRATIVE ASSESSMENT AND MODELING OF CAUSES OF HUMAN ERROR ON ROAD TRANSPORTATION

The research explored the potential causes of accidents in road transportation systems and developed a model to illustrate the interactions between these identified groups of causes of human error leading to road accidents [8.1].

Due to significant role of fatigue as root cause of many road accidents and its relationship with other categories of causes (i.e., vehicle, environment, human due to non-fatigue factors), this factor is highlighted and integrated with other causes [8.1].

Considering the characteristic of failures in vehicles, road environment, human due to fatigue and human due to non-fatigue factors, the stochastic approach is used to model the problem and predict the reliability/unreliability of road transportation systems at any given time [8.1].

In the Markov model presented, the constant values are assumed for the instantaneous failure rates of human error leading to accident due to vehicles, road, human fatigue, and non-fatigue human factors. This assumption originates from the fact that it is common to see just the constant failure rates in practice and in databanks. Moreover, the reliability of many components indeed follows exponential distributions with constant failure rates. However, the assumption of constant failure rates and consequently use of Markov model in this research can simply be disregarded such that the model be converted

into a series RBD model in order to obtain the reliability and risk of system incorporating time-varied failure rates for some or all of the contributing factors in the modeling.

The expected patterns and functions for instantaneous failure rates of human due to fatigue and vehicle are explored and presented. However, it is pointed out that there is a need for further research in the patterns of instantaneous failure rates in road environment and human due to non-fatigue factors over the time [8.1].

It is suggested that the failure rates for each of the categorized groups of causes can be estimated by the summation of failure rates of their constituting components [8.1].

In principle, the data regarding physical failure rate and human error rate for the constituting components of these identified categories of causes in road accidents shall be obtained from databanks, experiments, actual data, etc. and fed into the models and sub-models developed in this research [8.1]. This requires some organized, well designed and coordinated procedures in countries and across continents for collection, aggregation, analyses and presentation of data to the researchers, transportation authorities, law enforcement, etc. [8.1].

Furthermore, it is noted that the vehicle, road environment, and human due to non-fatigue factors may not only fail critically to endanger the safety of road transportation, but also the conditions of these factors could have impacts on the safety of transportation through enhancing the total level of driver's fatigue [8.1].

With continued improvement in design of roads and vehicle components by auto industries and transportation authorities, the failures rates of their related components and their impacts on the safety of transportation systems are going down day by day [8.1]. However, the conditions and characteristics of roads and vehicles impacting the driver's

fatigue are not improved automatically just because of improvement in the failure rates and safety impact of their components [8.1].

The recent trend in competition among auto makers is the lowering of drivers' mental and physical efforts through automation (e.g., cruise control, automatic gear-box) [8.1]. Although, this increase in the level of automation provides extra comfort for drivers, however, this may transform the form of fatigue from more over-load and dynamic type to more under-load and static one [8.1].

These new forms of fatigues in driving operation are expected to elevate the total fatigue level too mostly in form of boredom and static fatigue leading to deteriorated level of vigilance over the time [8.1]. Therefore, there is a need for further research to investigate the reliability of transportation systems under different degrees of automation in vehicles. Similarly, there shall be special considerations in design of road environment in terms of its effects on driver's fatigue level such that the design of roads should neither pose excessive workload on driver nor elevate the driver's under-load fatigue and boredom level [8.1].

There has to be further research on the impacts that human abilities, conduct, skills and interests would place on the level of driver's fatigue and as the result on reliability of transportation systems [8.1].

It is necessary to mention that the failure term used in this research is just covering the failures with such a severity and kind that result in drivers' error leading to accident. Therefore, the subject of grading of failures in terms of severity and type in light of severity of human error and its effects on potential or near-miss accidents and incidents demands further research [8.1].

8.2 RELIABILITY AND RISK ASSESSMENT FOR THE ADAS/PSS BASED VEHICLES

The potential error countering measures can be focused on such categories as driver error reduction (e.g., improved ergonomically designed vehicles, improved road environment design, training), the use of ADAS technologies to prevent or minimize risk of accidents in the event of driver's error, and finally the passive systems (e.g., seatbelts, airbags) in the event of failure in ADAS and driver's error/failure [8.2].

This research for the first time explored how these three groups of error counter measures interact in a vehicle system in terms of reliability of their individual and overall functions. It also has looked on how the failures in any combination of the constituting components of these three groups of counter measure systems affect the reliability of total system in light of occurrence of accidents [8.2].

The reliability prediction of vehicles equipped with ADAS and passive systems are mathematically determined at any given time by the models varying in the degree of complexity [8.2].

The research has developed general models that estimate the probability of accident as a function of time at the wheel, state of fatigue, road environment, and vehicle's ADAS and PSS. The findings of this research are expected to be used for examining and improving the reliability of system by auto industries, road transportation authorities, and the researchers [8.2].

With systematic collection and in depth analysis of data regarding accidents involving vehicles equipped with ADAS and Passive Systems and feeding them into such

assessment models and methodology as developed in this research, it is expected to have the lower casualties resulting from road accidents in the future [8.2].

The prediction and optimization modeling of the total reliability of road transportation system containing multi vehicles (different in degree, type and complexity of ADAS and PSS technologies), pedestrians, road infrastructures, drivers with different skills, etc. for developing best strategic decisions, regulations and directions on the road safety are yet to be investigated by researchers [8.2].

8.3 RELIABILITY AND RISK ASSESSMENT OF PEDESTRIANS

CROSSING ON ROADS

The research has focused on identification of causes of “pedestrian-to-vehicle accidents” on roads in systematic manner using fault tree and thorough review, analysis and development on the latest findings of research works in this area [8.3].

The author came up with novel methodology in systematic, flexible and stochastic modeling of the reliability and failure prediction of “pedestrian crossing” at any given time integrating all the contributing factors and parameters [8.3].

This research highlights the significance of multi facet approach in addressing the concern of pedestrian casualties in both developed and developing countries [8.3].

The importance of available databases containing detailed and processed failure rates in road transportation has been found essential [8.3].

The research has developed general models that estimate the probability of pedestrian-vehicle accident as a function of time at the wheel, environmental conditions, state of driver’s fatigue, vehicle’s ADAS and PSS, and pedestrian behavior and conduct.

In the Markov models presented, the constant values are assumed for the instantaneous failure rates of pedestrian error due to behavioral and road and infrastructure causes. This assumption originates from the fact that it is common to see just the constant failure rates in practice and in databanks and the fact that the reliability of many components indeed follows exponential distributions with constant failure rates. However, the assumptions of constant failure rates and consequently use of Markov models in this research can simply be disregarded such that the models be converted into series RBD models in order to obtain the reliability and risk of system incorporating time-varied failure rates for some or all of the contributing factors in these modeling.

The findings of this research are expected to be used by auto industries and transportation authorities to come up with the new vehicle and road based ADAS and safer and more protective pedestrian crossing zoning, devices and regulations.

Due to scarce data for instantaneous failure rates for basic components identified in this research, a future direction of research in overcoming the issue may be to obtain the failure rates of basic components affecting the safety of pedestrian crossing by fuzzy language and to make prediction on the reliability/failure of pedestrian crossing in fuzzy linguistic terms (e.g., H, L, VL, M) [8.3, 8.4, 8.5].

Furthermore, the grading in severity of “pedestrian crossing” failure and subsequently its reliability is another area that demands further research [8.3].

8.4 RELIABILITY AND RISK ASSESSMENT OF OLDER DRIVERS ON ROADS

There have been various approaches in attempting to reduce the risk of crash by older drivers including use of ADAS and road based technologies, licensing requirements, policing and special training programs [8.6].

The research identified and illustrated all the potential causes of crash by an older driver systematically using FTA to assist transportation authorities in investigation and reduction of the risk of crashes [8.6]. Furthermore, a novel methodology has been developed to better monitor the state of older drivers at any given time in light of workload and it can be used in further advancing the ADAS, specifically designed for older drivers, by auto industries and transportation authorities [8.6].

As per the methodology developed in this research, the human involved causes in potential crash, as shown in the related fault tree, can be monitored and assessed quantitatively in light of workload imposed on the driver at any given time, while driving using continuous/periodical objective and subjective feedback from older drivers' input and performance [8.6]. The state of workload shall be presented by in-vehicle technologies to the driver in form of voice/ and text or graph through a processor built on the methodology developed in the research.

In high risk situations, when workload reaches the threshold capacity of driver and no appropriate reaction is noticed from the driver, the vehicle can be programmed to override the control of vehicle [8.6]. There is possibility to program the in-vehicle technologies to communicate through in vehicle and on road technologies to traffic police/EMS/road assistance services and even to record the reactions of driver towards the warning received [8.6]. It is to be noted that the upper limit of certain variables in the conditions (Eqs. (5.1)-(5.5)) can be set as high as necessary (e.g., alcohol consumption, high

level of fatigue) in order to let the severity of a significant factor alone warn the driver or avoid him/her of further driving [8.6].

At the present, there has been no methodology and system in place to make an overall and accumulative assessment in an interactive way on the state of driver in terms of workload imposed by various personal, vehicle, and road factors [8.6].

Due to dynamic and complex characteristics of driving and its multi factors involved with human at the center and key element, the condition monitoring of such critical component of this driving process (i.e., older driver specifically with its already declined characteristics) in light of changing workload at any given time in interactive and systematic manner is seen essential [8.6].

The total risk calculation of severe crash by older drivers as the result of all potential causes (i.e., human and non-human causes) can also simply be calculated having the failure probability of crash event calculated using the FTA subject to availability of failure rate/probability data for those illustrated basic events in the FTA [8.6].

The author assumed for simplicity of the analyses that the workload imposed on the drivers caused by the factors shown in the fault tree are accumulated linearly, whereas the shape of accumulation of workload may take one or a combination of forms like linear, exponential or power depending on the person and the state and type of workload [8.6]. As per recent review by the author and other researchers in literature, there has been no conclusive finding on the proposed shape of fatigue accumulation letting us assume for simplicity of our research that the fatigue accumulates linearly over time [8.6].

The development of appropriately structured and built scoring systems with their relevant guidelines for assessment of older drivers' health, abilities and behavior by the

authorities, in-vehicle technologies, and older drivers for the parameters and variables defined in the conditions of Eqs. (5.1)-(5.5) are seen essential [8.6]. Therefore, it is expected that this research to trigger the need for placing new regulations and procedures for better protecting the older drivers based on the concepts developed in this research.

The use of linguistic FUZZY approach in building the conditions developed and the objective and subjective assessments of the drivers' state while driving can be another area for further research [8.6].

Finally, a potentially similar methodology used in the research can be developed and applied for novice drivers as another group of drivers demanding special attention by auto industries, transportation authorities, and researchers.

8.5 RELIABILITY AND RISK ASSESSMENT FOR YOUNGER DRIVERS ON ROADS

This research has identified and illustrated systematically and logically all the potential root causes of crash by younger drivers using FTA to better assist transportation authorities and researchers in investigation and reduction of the crash risk. Furthermore, an integrative prediction methodology has been developed to stochastically assess the risk state of younger drivers on roads at any given time [8.7].

As per author's proposed methodology, the risk state of driving by younger drivers can be assessed and monitored quantitatively by a central in-vehicle processor based on collected data. The processed information on total risk state shall be presented to the driver at a given time right in vehicle using the models (Eqs. (6.1)-(6.14)) developed in the research [8.7]. The data on risk state of each individual human related cause in risk of a

crash, as identified in Figure 6.1, is supposed to be collected objectively and subjectively from younger drivers, in-vehicle and on-road [8.7].

The subjective data to be collected from driver are related to those attributes of the driver that may vary day by day and time to time (e.g., alcohol consumption, emotion, fatigue) [8.7]. These kinds of data shall be collected based on a user friendly interface, perhaps audio and video, to be developed as an in-vehicle technology built on pre-developed questionnaires with appropriate scaling [8.7]. .

The other human related data (e.g., instantaneous failure rate of driver due to maneuvering skills) for the contributing causes of a crash can be collected off the vehicle by the transportation authority periodically as needed and then integrated into proposed central processor of system responsible for calculating the total risk [8.7].

Similarly, the failure data of physical components contributing safety of the driver as illustrated in Figure 6.1 shall be determined off the vehicle and then integrated into the central processor [8.7].

The author proposes that in the future every vehicle whether driven by young or old or skilled needs to be equipped with “riskometer” [8.7]. As the result, it is expected that every vehicle on the road can obtain and present the risk state of driving by its driver at any given time [8.7].

Furthermore, the risk related data and state of each vehicle on the road can be communicated to its adjacent vehicles, including the vehicle driven by a younger driver, using technologies that are currently being developed and used by the automotive research centers (e.g., [8.8]) [8.7].

The author's proposed concept on collection/presentation of data/information is expected to be the focus of further research works by the automotive industries and transportation authorities in order to fine-tune and develop these suggested methodologies in details and in the most applicable ways [8.7].

Nowadays, the younger drivers when they get to roads are just monitored and controlled by the law enforcement (e.g., random speed control by police), their parents and for some youths who can afford with ADAS technologies [8.7]. This research with its methodology and concept is proposing and emphasizing that besides these available measures, there must be a system that constantly monitors younger drivers in interactive way and give awareness to the youth and their passengers based on his/her total state of risk resulted from many contributing causes of a potential crash [8.7].

The policing of younger drivers on roads is nowadays appears to be the most influential way to prohibit this group of drivers from doing risky behavior [8.7]. Although this negative reinforcement measure would possibly remain as the most effective way for small group of youths, but the author believes that many of younger drivers would need some sort of more supportive, self involved and positive reinforcing way of approach in correcting their driving [8.7].

There are rooms for further research on the most effective procedures and mechanisms for objectively and subjectively collection of the human failure/risk data both in and off the vehicles [8.7].

Another area for further research is to identify the value and method of presenting the risks attributed to individual and groups of contributing causes of a crash rather than presenting just total risk [8.7].

8.6 The HRA-BASED ROAD CRASH DATABASES AND DISTRIBUTION

CHARACTERISTICS OF DRIVERS' FAILURE RATE

The methodologies proposed in the research for crash data collection, investigation, maintenance, presentation, and analyses have been derived from the latest research in human reliability assessment for road crashes by the author.

It is expected that the findings of this research to be well received and utilized by transportation authorities and auto industries in absence of any available HRA-Based road crash database for betterment of their safety preventive measures whether in form of policies or technologies.

The proposed structural formats of “HRA-Based Road Accident Investigation & Data Collection Form” (Fig. 7.3) and “Human-Centered Reliability Data-Bank for Accidents in Road Transportation” (Fig. 7.6) can be revisited by the transportation authorities as per their discretion and ease of use and maintenance by investigators and analysts [8.9, 8.10].

However, the principles and foundations of the forms (Figs. 7.3 & 7.6) are unique paving the ways for systematic, deep, and driver-centered analyses of collected data for safety enhancement of road transportation [8.9, 8.10].

As the percentile methodology used in the proposed databank (Fig. 7.6) is a novel approach in developing and presenting failure data, thus the reliability/failure databanks already in place and use in other industries and applications are expected to use this methodology to provide more detailed analytical information [8.10].

The findings on other part of research which focused on the driver's failure characteristics shall also give an insight to Human Reliability Assessment experts to make

accurate assessment and prediction on the driver's failure before and after exhaustion point and to design the appropriate preventive measures [8.9, 8.10].

Due to the significant risk associated with driving beyond the exhaustion point of driver (Figures 7.4 & 7.5), it was decided not to repeat the test in large number of runs [8.10]. Therefore, conducting tests in large number of runs can be the focus of future research in a lab setting using a simulator technology [8.10].

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Chapter 7-The HRA-Based Road Crash Data: A Methodology for Crash Investigation and Validating the Distribution Characteristics of Driver's Failure Rate (*References*)

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Chapter 8-Discussions, Conclusion and Future Directions (*References*)

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