EFFECTS OF VELOCITY, TEMPERATURE AND RAINFALL ON THE FRICTION COEFFICIENT OF PNEUMATIC TYRES AND BITUMEN ROADS

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A thesis submitted in the fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Automotive Manufacturing and Mechanical Engineering

June 2014
Certificate of Authorship

This thesis contains no material, which has been accepted for the award of any other degree or diploma in any university, unless stated. To the best of my knowledge the text of this thesis is original and contains no material previously published by any other person, except where due references are made in the text.

Jenelle Catherine Hartman
Dedication

“Words cannot express the heartache, pain and loneliness I feel everyday. I don't live any more, I only exist.”

Helen Crichton
Mother of Ebony Dunsworth, aged 16
Tragically killed on Victorian Roads, October 2011

This thesis is dedicated to all who have lost their lives or been seriously injured in motor vehicle collisions, and their families and friends who live with the physical and emotional pain of their loss, every day...
Acknowledgements

First and foremost I am sincerely thankful to my supervisor Professor Reza Jazar, the Discipline Head of Mechanical and Automotive Engineering, RMIT, Melbourne, for his motivational guidance and constructive criticism throughout my research work and in the writing of my dissertation. His continual contributions and advice assisted me to maintain both focus and drive throughout my research.

I would also like to thank my associate supervisor Associate Professor Firoz Alam, the Deputy Head of School, School of Aerospace, Mechanical and Manufacturing Engineering, RMIT, Melbourne, for his treasured input and valuable suggestions throughout my research but particularly during my research planning phase. The advice provided by Associate Professor Alam ensured my work maintained relevant direction and focus.

The final product of my work would not be what it is without my proof reader Anna McArthur. Her professionalism and eye for detail were perfect to assist me in completing my work to such a polished standard. I thank her for taking the time out of her own day and busy life to assist me in achieving my dream.
I am highly grateful to my employer, Victoria Police, and my supervisors Bernie Rankin, Jeff Smith, Brad McArthur and Gerard Clanchy for their ongoing support of my research. Practical testing would not have been possible without the use of fleet vehicles and brake testing equipment provided by Victoria Police. I extend my gratitude to members of the Major Collision Investigation Unit, Amma Bridgeman, Brendan Butland, Mark Amos, Rohan Courtis, Robert Cunningham, Phil Frith, Tony Gentile, Rob Hay, Matt Hunt, Aaron Ibbott, Dave Mair, Shane Miles, Darryl Out, Fletcher Pearson, Michael Hardiman, Lindon Walker, Trevor Collins, Dave Morris, Chris Carnie, Ben Howie, Col Schmidt, Wayne Reynolds, Roz Wilson and Brendan Smith, all of whom enthusiastically assisted me over three years of field testing and report writing, not only practically but emotionally.

I am also thankful to the Country Fire Authority and in particular the Operations Officer and State Driving Coordinator, Glen Jennings, for his support with the simulated rainfall testing. The unlimited use of the Fiskville Training Centre and pumper trucks provided a perfect environment to conduct controlled rainfall testing that would otherwise have been impossible. No request was ever too much and his support will never be forgotten.
I am forever indebted to my precious son, Jett, who suffered a lot during my hours at the computer when he would rather me be spending time with him kicking footballs or shooting hoops. To both my parents who never questioned caring for Jett while I conducted research or continued to write my dissertation and for their financial assistance over six long years whilst I completed both my Bachelor and Research degrees, I can never thank you enough. Finally, I conclude with the most special thank you to my husband, Brett, for his patience and unwavering support for the last six years of extensive study. This work could never have been completed without his unconditional support and perseverance.
ABSTRACT

A world without friction would be a world of destruction. Friction is a consequence of the laws of physics. The laws of motion and friction predict that kinetic friction will not be affected by velocity, ambient temperature or rainfall. This hypothesis developed hundreds of years ago is based primarily on research of objects and surfaces with metallic properties. Pneumatic tyres on motor vehicles have viscoelastic properties and were not commercially exploited until after 1950. Since their development, researchers have identified that polymers such as pneumatic tyres have a tendency not to follow the laws of friction.

Research into the friction coefficient of pneumatic tyres and road surfaces is very new and remains contradictory and elusive as both road surfaces and vehicle design continues to develop. Vehicle safety, road design and collision investigation relies greatly on accurate determination of tyre and road surface friction. This study is designed to determine the effect of vehicle velocity, ambient temperature and rainfall on the friction coefficient of pneumatic tyres sliding on bitumen road surfaces. Where an effect is identified, formula will be developed to facilitate the prediction of friction to stabilise such effect.
To determine the effect of velocity, temperature and rainfall on the friction coefficient of pneumatic tyres and road surfaces, three series of tests were undertaken. Skid resistance tests were performed in a passenger vehicle on bitumen roads at a range of speeds between 30 km/h and 80 km/h, with and without antilock braking, at a range of temperatures between 3°C and 43°C and pre, during and post rainfall. The friction coefficient of the pneumatic tyres and roads surfaces for each variable was determined using an accelerometer.

Results identified that when a vehicle skids with antilock braking, the friction coefficient of the tyres sliding on the road surface will increase as velocity increases. When a vehicle skids without antilock braking, the friction coefficient will decrease with increasing velocity. As temperature increases from 3°C to 43°C, the friction coefficient increases linearly. The friction coefficient of tyres sliding on a road surface at 60 km/h will increase in periods of heavy rain and decrease on a wet road after a period of rainfall, in comparison to dry road friction.

A solution was developed to facilitate friction coefficient prediction. Where any analysis of the friction coefficient of pneumatic tyres sliding on road surfaces is necessary, the developed models can be used to account for
any variation due to velocity and temperature. If the friction coefficient of a vehicle sliding on a bitumen road at 3°C is identified, then it is possible to predict what the friction for the same vehicle sliding on the same road at any other temperature using the prediction models. A similar model was developed to account for changing vehicle velocity. Prediction models were not developed for rainfall. The testing procedure did not facilitate the ability to quantify the effect of rainfall and therefore a method of prediction was not possible. A need for innovative ideas would be necessary to quantify the effect of rainfall on friction of pneumatic tyres and road surfaces.

This research will provide valuable information for road design engineers and collision investigators worldwide regarding the effects of vehicle velocity, ambient temperature and rainfall on the friction coefficient of motor vehicle tyres and road surfaces. The findings have the potential to increase road safety and advance collision reconstruction and investigation.
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>RMIT</td>
<td>Royal Melbourne Institute of Technology</td>
</tr>
<tr>
<td>°C</td>
<td>Degrees Celsius</td>
</tr>
<tr>
<td>km/h</td>
<td>Kilometres per hour</td>
</tr>
<tr>
<td>ABS</td>
<td>Antilock Braking System</td>
</tr>
<tr>
<td>CFA</td>
<td>Country Fire Authority</td>
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<tr>
<td>WHO</td>
<td>World Health Organisation</td>
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<tr>
<td>WBL</td>
<td>Warrnambool Bus Lines</td>
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<tr>
<td>MPH</td>
<td>Miles per hour</td>
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<tr>
<td>SCRIM</td>
<td>Sideways coefficient routine investigations machine</td>
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<tr>
<td>NSW</td>
<td>New South Wales</td>
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<tr>
<td>G</td>
<td>g force</td>
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<td>seconds</td>
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<td>millimetre</td>
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<tr>
<td>m</td>
<td>metre</td>
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<tr>
<td>µ</td>
<td>friction coefficient</td>
</tr>
<tr>
<td>F</td>
<td>Fahrenheit</td>
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<tr>
<td>GMH</td>
<td>General Motors Holden</td>
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<tr>
<td>PSI</td>
<td>Pounds per square inch</td>
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<tr>
<td>Abbreviation</td>
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<tr>
<td>Pa</td>
<td>Pascal</td>
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<tr>
<td>R</td>
<td>radius</td>
</tr>
<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
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CHAPTER 1: INTRODUCTION

1.1 OVERVIEW

Road surface friction is a significant factor in the slowing efficiency of a braking or sliding vehicle. Road authorities apply well-defined procedures in their design and production of roads in a quest for lower collision rates and safer roads.

Globally, collision reconstructionists and investigators work to determine how and why motor vehicle collisions occur. A critical element of any analysis is to determine the friction coefficient of the vehicle tyres and the road surface under rolling and sliding conditions. Due to the unexpected and dynamic nature of road trauma, it is not possible to determine the road surface friction in conditions identical to those occurring at the time of the collision. Post collision skid resistance determination may be invalid or unreliable if sliding friction coefficient is affected by velocity, temperature and rainfall, subsequently resulting in fallacious collision analysis.
The effects of inaccurate collision analysis can be detrimental, potentially leading to prosecution of drivers for offences they did not commit, or alternatively road development and design which is inappropriate or unsuitable for the location or conditions, making them unsafe or lethal.

Currently collision analysis relies on knowing or estimating the road surface friction skid resistance levels, which are determined post incident/collision. If the conditions at the time of testing are different to those occurring at the time of the incident/collision then the results may be inaccurate. This study will examine the effect of velocity, temperature and rainfall on the friction coefficient of pneumatic tyres and road surfaces.

Where velocity, temperature or rainfall is determined to affect the sliding friction of pneumatic tyres and road surfaces, then models will be developed which will facilitate the ability to predict the friction coefficient for a given vehicle velocity or temperature using a result obtained at another velocity or temperature.

The ability to predict the friction coefficient will significantly improve the accuracy of collision reconstruction and analysis, and the
increased understanding of road/tyre surface friction will ensure that road design and construction becomes safer for all road users. A difference of 10% on the friction coefficient can result in a speed analysis that is wrong by up to +/-8 km/h at 60 km/h.

1.2 PRIOR WORK

A thorough examination and review of literature related to the friction coefficient of pneumatic car tyres and road surfaces highlighted a number of issues that were either contradictory or limited in their scope. The laws of friction often do not hold true for rubber products. Interest in the friction of pneumatic car tyres and road surfaces is only new and accordingly there are many areas that are simply not understood. The laws of friction developed by Coulomb told us that the friction between two rigid bodies is independent of temperature and velocity. In 1952 Schallamach determined that rubber does not follow Coulombs theory however the research of Schallamach relates to rubber compared to rigid bodies researched by Coulomb when he defined his theory. Multiple researchers who have identified that tyre/road friction decreases non-linearly with increasing temperature have supported
Schallamach and his findings. Heinrichs (2003), and Shah and Henry (1978) have all performed extensive research specifically looking at the effects of vehicle velocity on road/tyre friction coefficient, but their research is also contradictory. What can be surmised from their work is the road/tyre friction is dependent on vehicle velocity. Common sense would suggest that lubricants such as water would decrease the friction coefficient between two surfaces. However, in 2001 Claeys, Alvarez, Horowitz, Canudas and Richard identified that the depth of water is critical to establish what effect water will have as a lubricant on road/tyre friction. Their work and results highlighted the need for further and more specific research relative to car tyres and road surfaces. This was further supported using laboratory testing by Blythe in 2013. Blythe identified a need for real world testing to validate their findings.

1.2 RESEARCH GAP

Essentially there remain two areas, which can be considered as gaps within the research area: contradiction and specificity. There is literature published which supports that velocity, temperature and rainfall do affect the friction coefficient of two surfaces, while there
is equally published literature which identifies that the friction coefficient of two surfaces is not affected by velocity, temperature and rainfall. It is evident that the chemical make up of the two surfaces in contact are the most important variables in determining the friction coefficient of any surfaces in contact. It is clearly apparent that to determine whether velocity, temperature or rainfall affect the friction coefficient of pneumatic tyres and bitumen road surfaces the research must be performed using pneumatic tyres and bitumen road surfaces. Current research by Blythe (2013) and Claeys et al. (2001) using the two relevant surfaces is laboratory based, which always increases the risk of peripheral influences. There is a need for research, which is conducted to determine the friction coefficient of pneumatic tyres and road surfaces using a sliding an actual motor vehicle on a used bitumen road surface to validate the previous findings.
1.4 RESEARCH AIM AND OBJECTIVES

1.4.1 AIM

The research aims to explore the influence of environment factors and vehicle variables on the friction coefficient of motor vehicle tyres and paired road surfaces, with a focus on rainfall, ambient temperature and vehicle speed.

1.4.2 OBJECTIVES

• To identify whether a change in ambient temperature affects the friction coefficient of motor vehicle tyres and bitumen road surfaces
• To establish whether the influence of temperature on the friction coefficient of tyre and road surfaces is more radical on wet or dry road surfaces
• To determine the effect of rainfall on the friction coefficient of vehicle tyres and road surfaces
• To establish the effect of vehicle velocity on the friction coefficient of vehicle tyres and road surfaces
• To determine whether any vehicle velocity effect is influenced by antilock braking systems (ABS)

• Use experimental data in mathematical modelling to validate the results
1.5 HYPOTHESIS

Three hypotheses have been defined. The purpose of this research is not to test the hypothesis to either accept or reject it but rather report exploratory research so as to make conclusions and recommendations to increase understanding of the subject area and identify necessary future research.

HYPOTHESIS 1

*The friction coefficient of motor vehicle tyres and paired road surfaces is not affected by ambient temperature.*

HYPOTHESIS 2

*The friction coefficient of motor vehicle tyres and paired road surfaces is not affected by vehicle velocity.*

HYPOTHESIS 3

*The friction coefficient of motor vehicle tyres and paired road surfaces is not affected by rainfall.*
1.6 RESEARCH QUESTIONS

There are several questions, which provide the scope for the purpose and objectives in striving to resolve the thesis:

(1) *Does the friction coefficient specific to pneumatic tyres and road surfaces obey the laws of friction relating to rigid bodies when considering the effects of velocity, temperature and rainfall?*

(2) *Can friction coefficient of pneumatic tyres and road surfaces be predicted in instances of conditional effect?*

The research questions were developed with the second set of questions dependant upon the research findings of the first set of questions. The first set of questions focuses on the effects of three variables: vehicle velocity, temperature and rainfall on the friction coefficient of pneumatic tyres and road surfaces.

(1) *Is the friction coefficient of pneumatic tyres and paired road surfaces affected by velocity?*
(2) Is the friction coefficient of pneumatic tyres and paired road surfaces affected by temperature?

(3) Is the friction coefficient of pneumatic tyres and paired road surfaces affected by rainfall?

(4) Can the friction coefficient of pneumatic tyres and paired road surfaces be predicted to account for the effect of velocity, temperature and rainfall?

The second set of questions is dependent upon the research findings from the first set of questions. If any or all of the questions can be affirmed then consideration should be given to whether a model can be developed to facilitate the prediction of friction relative to the variables affirmed to have an effect. If the questions in the first set are not sustained, then any analysis in an effort to develop models to predict friction coefficient become inapt.

(1) Can the friction coefficient of pneumatic tyres and paired road surfaces be predicted where a change in velocity is identified?
(2) Can the friction coefficient of pneumatic tyres and paired road surfaces be predicted where a change in temperature is identified?

(3) Can the friction coefficient of pneumatic tyres and paired road surfaces be predicted where rainfall is determined to be a relevant factor?

1.6 SIGNIFICANCE

The study contributes significantly to tribology and the greater understanding of the friction coefficient of two sliding surfaces, specifically rubber, and in addition provides considerable advancements in collision reconstruction and road safety worldwide.

Firstly, a clear understanding about how the friction coefficient of pneumatic tyres and road surfaces is affected by velocity, temperature and rainfall in ‘real world’ application, will enhance the knowledge and understanding of the unusual scientific phenomenon. Previously developed theories that are not specific to the properties of rubber have been applied to assist in
determining an anticipated outcome. This study will remove the ‘guesswork’ and provide proven outcomes.

Secondly, the research will facilitate the ability to predict friction coefficient in circumstances where velocity, temperature and rainfall have been determined to be a relevant factor. The ability to predict the friction coefficient will be momentous in the work of collision reconstructionists and road engineers alike. The enhanced knowledge will increase the accuracy when determining how and why road collisions have occurred.

The World Health Organisation (WHO) reports that 1.27 million people are killed globally each year as a direct result of motor vehicle collisions. Motor Vehicle accidents are the number one cause of death for those aged 10 to 24 years and the tenth highest cause of death behind natural causes such as heart disease and cancers. The impact of road safety and road deaths is increasing and is a global problem. An increased understanding of friction and how it impacts motor vehicle collisions will enable better understanding of how, when and why collisions occur and that in turn will assist in road design and road safety strategies aimed at reducing the associated devastation.
The results of this study will be available publicly to ensure the information is distributed and disseminated globally, ensuring the greatest benefits come from it. Road safety is everybody’s problem. Striving to improve our knowledge and understanding in this area is critical.

1.7 PUBLICATIONS

1.8.1 CONFERENCE PAPERS

The following conference papers were presented at friction and road safety conferences. The publications provide both exposure and feedback, which contribute significantly to the future of analysis and safety in tyre and road design and collision investigation.


1.8.2 JOURNAL ARTICLES

The following article has been accepted for publication in the Journal of *Nonlinear Engineering Modeling and Application*. The journal aims to provide publications that examine nonlinearities of engineering systems and will facilitate further learning and understanding of the primary research performed.

1.8 THESIS OUTLINE

• **Chapter 2:** *Road Surface Friction – A Case Study* provides an insight into motor vehicle tyre and road surface friction and why the research is both relevant and important. The chapter provides a detailed synopsis into a fatal bus collision that occurred in rural Victoria in 2009. Details will include how the collision occurred and the investigation that followed, including the identification of the road surface friction coefficient as the significant factor resulting in the death of three young lives. The investigation demonstrates just how important understanding road/tyre friction is to both road safety and collision investigation in the future. The enormity of fatal collisions is realised by the inclusion of the victims circumstances reminding us that road safety is important to everyone.

• **Chapter 3:** *The Literature Review* defines and examines theory and research central to developing and defining the thesis. The topics include friction, the laws of friction, sliding friction, rubber friction, road surface texture, factors affecting friction including temperature, lubrication and velocity, hydroplaning and the
relevance of friction to collision reconstruction. The topics are described below:

- History and current research into friction including the development of the scientific field and the relevant laws. The conflicting research and theories are highlighted providing strong evidence that friction is surface specific and general laws cannot be applied to all surfaces.

- Sliding Friction considers the differences between static and kinetic friction and how laws and principles for friction are different for the two. Similar to friction in general the review identifies that friction analysis must be circumstance specific otherwise contradictory results may be observed.

- Rubber friction describes the recent developments and theories relating to rubber friction specifically. Consideration is given to what is essentially a very new sub study with pneumatic tyres having only been developed within the past sixty years.

- Road surface texture discusses the paired surface being considered within this research. It considers the macro and micro surfaces and how this influences the friction coefficient when combined with a subsequent surface.
Temperature identifies research and contradictory findings relevant to the effects of temperature on the friction coefficient of car tyres and road surfaces. It considers both the general and specific effect and how opinions have evolved. This section is specific to develop Chapter 3.

Lubrication also covers both general and specific theories considering the effect of lubricants, including water, on the road/tyre friction coefficient. Theories relevant to both water, rainfall and water depth are discussed but also provide conflicting opinions.

Velocity validates the motivation for Chapter 4 and discusses the theories and previous research relevant to the effect of velocity on friction coefficient both as a general theory, and additionally, specifically relative to motor vehicle tyres and road surfaces.

Hydroplaning is a phenomenon that is often volunteered as an explanation for uncontrolled vehicles sliding on road surfaces. Particularly with relevance to Chapter 5 Rainfall, the occurrence of hydroplaning and the related theories have been explored here.
• **Chapter 4:** *Vehicle velocity and its affect on friction* examines specifically how the velocity a vehicle is travelling at the commencement of skidding or sliding, effects the friction coefficient of the vehicle tyres and road surface during sliding. The chapter includes methodology, results, discussion, prediction model theory and future research. The results of a vehicle skidding with antilock braking (ABS) were compared to a vehicle without ABS. Analysis of the results determined that the effect with and without ABS is equal and opposite but an obvious effect is observed between 40 km/h and 80 km/h. Using the results, models were devised to facilitate friction prediction where velocity is determined to be a relevant factor in friction determination. Limitations and further research is discussed within the chapter.

• **Chapter 5:** *Ambient temperature and its effect on friction* was studied over three years with analysis temperature range from 3°C to 43°C. One hundred and eleven skid resistance tests were performed for analysis. The chapter includes methodology, results, discussion, prediction model theory and future research. The analysis identified a positive relationship between temperature and the friction coefficient. As temperature increased the friction
coefficient increased. A model was devised using the results to facilitate the prediction of the friction coefficient where ambient temperature is identified as a relevant factor.

• **Chapter 6:** *Rainfall and its effect on friction* was observed in circumstance of simulated rainfall using high-pressure fire fighting equipment. Comparison was made between dry, wet and raining conditions. The chapter includes methodology, results, discussion and research limitations. The results of the research identified that in periods of heavy rainfall the friction coefficient of pneumatic tyres will increase compared to dry or wet conditions. The study was performed in motor vehicles where there was no ability to quantify the results which could facilitate prediction. The results are significant in comparison to previous research.

• **Chapter 7:** *Conclusions* evaluate the research questions and define future directions in the area of friction coefficient related to pneumatic tyres and bitumen road surfaces. Critical evaluation of the research and its reliability and the scope for further advancements and validation are outlined in this chapter.
2.1 WHY DOES ROAD FRICTION MATTER

Around the world, collision investigators and reconstruction experts are able to accurately identify the cause of serious injury and fatal collisions in most circumstances. Driver error is determined to be the sole or significant contributing factor in most collisions. When collision reconstruction experts attended at the scene of the triple fatal collision on the Princess Highway, Heathmere, on 16 April 2009, the cause of the collision was not immediately clear.

Initial investigation approaches concentrated on vehicle speed, driver fatigue and driver error, all of which were eliminated. More than twelve hours after the collision, skid resistance tests were performed at the collision scene. The tests produced significant variations in results within a small test area of road. The results fell well below recommended investigatory levels. If contributing environmental factors, including road surface friction levels are not identified and rectified then there is
substantial risk that the collision will occur again, in addition to the risk that innocent drivers being incorrectly prosecuted.

In 2004, investigations into a single fatal collision at the same location did not examine the skid resistance levels at the site. Since 2004, inadequacies in road surface condition at the site were identified and partial repairs were made in the area. The serious risks involved with poor road surface skid resistance, variation in skid resistance levels in a small area and the extreme weather conditions were each underestimated and ultimately contributed to a tragic collision in 2009, when three innocent lives were lost.

2.2 A CHOICE BETWEEN LIFE AND DEATH

On 16 April 2009, a triple fatal collision occurred on the Princess Highway, Heathmere, Australia. On the fateful evening, the experienced driver safely negotiated the 53 seat coach and with eleven unassuming passengers around a right curve before continuing into a straight section of road where the driver unexpectedly lost control of the vehicle. The coach speared onto the incorrect side of the road and into the path of an oncoming vehicle. The driver of the coach input a severe left manoeuvre in an attempt to avoid colliding with the oncoming vehicle. The steering
input by the driver led to a subsequent roll over of the coach. During the rollover, five passengers were ejected. 3 of the ejected passengers, including a two-year-old child and her heavily pregnant mother, sustained fatal injuries. The deceased mother was seven months pregnant.

The author, a collision reconstruction expert with Victoria police attended the collision and identified a number of choices which had been made that ultimately led to the death of three people.

The road surface was identified as a significant contributing factor in the collision due to skid resistance levels that fell well below investigatory levels. In 2004, a single fatal collision occurred at the same location. The cause of that collision was not determined at the time. The decision was made to provide a partial repair of the road after the 2004 collision as a result of council assessments, which determined lower than expected skid resistance levels. A full repair was recommended but reduced due to very high costs associated with the maintenance. The partial repair resulted in the road having a number of different skid resistance levels in a small area. The risks of having areas with multiple skid resistance levels are underestimated. The summer months of 2009 in Australia, which preceded the collision, were extreme in high temperatures leading to further degradation of the road surface and resulting in significant polishing and bleeding on the high traffic volume road. The extensive wear damage
combined with the areas of multiple skid resistance levels and light rain provided conditions that were unforgiving on 16 April 2009. The three passengers who died were not wearing seat belts. Seat belts were fitted to all seats on the coach.

2.3 VICTIMS

All twelve occupants of the bus including the driver and eleven passengers sustained injuries of a varying degree. Three passengers sustained fatal injuries and died at the collision scene. One male passenger sustained serious injuries, which required ongoing treatment and care. The remaining eight passengers, including the driver, were conveyed to hospital for treatment for a range of minor injuries. Aside those physical injured in this collision there are so many other victims. Mothers lost daughters and granddaughters, Fathers lost sons, and husbands lost wives. There are so many victims when it comes to road trauma. Most of the victims from this and all other fatal collisions are not physically injured.
2.3.1 SABRINA BRADY

At the time of the collision, Sabrina Brady was nineteen years of age. Sabrina had been to Melbourne for the day to visit her mother. Sabrina was seven months pregnant and was also travelling with her two year old daughter, Maddision. Sabrina was returning home to her partner with whom she resided. Sabrina was seated at the rear of the bus with Maddison asleep with her head on her mums lap. Sabrina sustained chest injuries in the collision and died at the scene after been thrown from the vehicle during the rollover. She was not wearing a seatbelt. Sabrina’s unborn child also died as a result of the collision.

2.3.2 MADDISON DOBIE

Maddison Dobie was just two years of age at the time of her death. Maddison had travelled to Melbourne with her mum, Sabrina, to visit her grandmother. They were returning home when the collision occurred. Maddison was asleep on the rear bench seat of the bus with her head resting on her mother’s lap when the collision occurred. Maddison was thrown from the bus during the rollover and died at the collision scene.
from head injuries. Maddison was not wearing a seatbelt at the time of the collision.

2.3.3 JUSTIN POMERY

Justin Pomery was a twenty-year-old student from Heywood when he was tragically killed. Justin had been studying in Bendigo and was returning to his home in Heywood. He boarded the bus in Warrnambool. Justin selected a seat towards the middle of the bus on the driver side. Justin was partially ejected from the bus during the rollover and died from head injuries. He died at the collision scene. Justin was not wearing a seatbelt when the collision occurred.

2.3.4 LEIGH HOGGAN

Leigh Hoggan was a twenty five year old man who boarded the coach in Warrnambool to return to his home in Heywood. Hoggan had been to Warrnambool for the day to visit his children. Hoggan had been seated on the driver side of the bus until they stopped in Port Fairy at which time he changed seats to the passenger side of the bus. Hoggan was wearing a
seatbelt when the collision occurred. Hoggan suffered a fractured vertebra in his neck and was conveyed to the Alfred Hospital Trauma Unit for treatment. In the most part, Hoggan has now recovered from his physical injuries. Emotional injuries are much harder to overcome.

2.4 THE DRIVER

Mr Maxwell Shayler was aged fifty-seven years on the evening that he was driving the Iveco Coach from Warrnambool to Mount Gambier. An experienced coach driver, Mr Shayler held a full and unrestricted Bus Drivers Licence and had been working for the same company in the two years preceding the collision without incident. A local resident, he was familiar with the road and the conditions and drove accordingly. Mr Shayler was deemed fit for his work as a driver of heavy vehicles and suffered from no medical condition, which may have reduced his ability to drive at a high standard. Despite his own injuries sustained in the collision, Mr Shayler assisted both injured and uninjured passengers from the bus after the collision. Medical examinations conducted after the collision determined that Mr Shayler was not affected by drugs, alcohol or fatigue and was not affected by any medical condition which may have caused or contributed to the collision.
2.5 THE VEHICLE

Warrnambool Bus Lines (WBL) purchased the Euro-3 bus chassis from manufacturer Iveco in 2006. ‘Coach Design’ had built the body of the bus and it entered service in November 2006. The bus was licensed to carry fifty-three passengers. It was intended for distance passenger travel on the V Line run between Warrnambool and Mount Gambier and was known within the fleet as bus 38.

Post collision, a fully qualified forensic mechanic performed a mechanical inspection on the bus. It was concluded that prior to and at the time of impact, the vehicle as inspected would have been classed as being in a roadworthy condition. In particular all suspension components were in good serviceable condition. The vehicle had been mechanically well maintained.

The bus sustained extensive damage during the rollover collision including shattering of all the windows on the right side of the vehicle (driver side).
2.6 THE ROAD

The Princes Highway, Heathmere is a two lane, two-way country road that runs between Warrnambool and Mt Gambier in rural Victoria, Australia. The area is surrounded by large farming properties. The opposing lanes of the highway are divided by a painted double white line, which prevents legal over taking in both directions. The road runs in a general north to south direction however there are numerous bends along its length. The road has a speed limit of 100 km/h (62 mph) for all vehicles travelling in both directions. Predominantly the road is used for long distance travellers and large transport vehicles. The collision occurred about 100 km (62.1 miles) from Warrnambool in a small country area of Heathmere. Heathmere is prone to extreme hot temperatures in Summer (40°C +) and extreme cold temperatures in Winter (-0°C). The extreme weather conditions combined with prevalence of high speed and heavy vehicles left the road suffering from extensive bleeding and polishing. Some areas of the road had undergone repair resulting in multiple areas with significant variation in skid resistance levels.
2.7 COLLISION

At about 6:40 p.m. on Thursday 16 April 2009, the Austral passenger coach was being driven between Warrnambool and Mt Gambier. It had been raining but the rain was easing. The roads were wet and it was dark.

The bus was travelling at about 100 km/h before the driver reduced his speed to around 90 km/h whilst negotiating a right curve leading to a straight section of road with a mild decent. The bus was negotiated safely around the curve and commenced the straight section of road when the rear of the bus suddenly ‘skipped out’. The bus slid across the centre dividing line of the road and into the oncoming lane without any steering input by the driver. The bus was almost wholly on the incorrect side of the road and approaching a vehicle travelling in the opposite direction. The driver of the coach then input a left steering manoeuvre in an attempt to avoid a head on collision with the oncoming vehicle and also return the vehicle to the correct side of the road. As a result of the steering manoeuvre, the bus commenced to yaw. It rotated in an anticlockwise direction whilst crossing back into the northbound lane. The front of the bus continued onto the bitumen shoulder and the bus was almost 90° to the travelling direction when it tripped and commenced to roll onto the driver side of the vehicle. The bus rolled onto the right side causing all
unrestrained passengers to be thrown across or out of the vehicle on the driver side. The bus continued to slide onto the driver side whilst rotating in an anticlockwise direction before coming to rest on the grass reservation on the west side of the road facing south. The bus remained on the driver side.

When the bus first commenced to yaw it was travelling at a maximum of 73 km/h. An onboard visual recording of the driver identified the sudden loss of control of the bus without any input of the driver. From the recording it was evident that the driver was awake and alert.

2.8 COLLISION CHRONOLOGY

There was an extensive crash history at the site between 2004 and 2009. Sadly this was not the first fatal collision to occur at this location. In June 2004, a semi trailer and prime mover combination rolled on the same curve resulting in the death of the single occupant/driver. The cause of that collision was never identified.

In August 2004, Vic Roads conducted an inspection of the site due to the fatality in June. ‘Slippery when wet’ signs were installed and sideways
force co-efficient routine investigations machine (SCRIM) testing requested. The SCRIM testing was performed in September 2004 and revealed skid resistance values below the Vic Roads investigatory level. This led to a further full site inspection in October 2004, which identified significant texture loss. A bid for funding to reseal the road was launched in December 2004. The bid was successful and the works were scheduled for March 2006.

In March 2006, the reseal was performed however an error in the bidding process meant that the reseal was 130 metres short of what was previously identified as required for the site. A further bid was made to complete the 130 metres in Spring, 2006 but unfortunately the short section of reseal failed to attract funding. A subsequent pavement study in July 2007 indicated that the road ‘roughness’ and wheel rutting was moderate. In Spring of the same year the 130 metres of road that had not undergone reseal was identified as being in poor condition and in need of water blasting treatment. In February 2009, the 130 metre reseal was completed. This area of reseal was immediately north of the subject crash location. The road immediately south of the coach at rest had undergone repair in this reseal.
In April 2009, the triple fatal collision involving the Austral coach occurred. The next day the speed limit in the area was reduced to 80 km/h. On 17 May 2009, one month after the bus rollover, a paper delivery truck lost control upon entering the same right bend. The reason for the loss of control was unclear but speed was not believed to be a contributing factor.

On 26 May 2009 a SCRIM testing vehicle from NSW was transported to Victoria to test the collision site. The test revealed various surface friction results at the site. Post testing, the entire site was water blasted. Subsequent SCRIM tests the day after water blasting revealed significantly increased surface friction values as a result.

2.9 SKID RESISTANCE TESTS

Vic Roads are responsible for the regulation of road conditions and standards in the State of Victoria. Vic Roads provide recommended skid resistance levels based on various site categories. Henty Highway, Heathmere at the collision location is categorized as a category 2 site. Site category 2 includes curves with a radius equal to or less than 250 metres, gradients of 5% or steeper and 50 metres or longer freeway on/off ramps. It is recommended that site category 2 have a recommended
investigatory skid resistance level of 0.50 with allowable risk rating adjustment zones of 0.45 to 0.60.

At about 8:00 a.m. on Friday the 17th April 2009 a series of skid resistance tests were conducted at the collision location. All tests were performed whilst travelling north in both the north and south bound lanes in addition to a combination of both. At the time of testing the road was wet as a result of persistent rainfall since the collision. Based on information received it was likely that the condition of the road was very similar to what it was at the time of the collision when skid resistance tests were done. Two series of tests were performed. Initially tests were conducted in a VE Holden Omega, a large family sedan (Fig 2.1 – Fig 2.4). The test series was then repeated at 9:10a.m. in a 1989 Austral passenger bus (Fig 2.5 – 2.7).

2.9.1 VERICOM BRAKE TEST COMPUTER

Skid resistance levels were measured using a VC4000 Brake Test Computer fitted into the vehicles. The same device was used for both test series. A brake test computer is essentially an accelerometer, crystal clock and microcontroller. The accelerometer measures the acceleration
whilst the test vehicle is under braking. The crystal clock measures the length of time that the vehicle is under braking. The microcontroller calculates the vehicle velocity 100 times per second. With velocity and time known, the microcontroller calculates distance 100 times per second. With acceleration, time and distance known the skid resistance of the test surface can be determined.

2.9.1.1 ACCELEROMETER

Three plates, A, B and C are suspended. Plate B is a mass suspended by springs between plate A and plate C. At zero G’s, plate B is equivalent from plate A and place C. When the brakes of the vehicle are applied by the driver the vehicle will pull negatives G’s and plate B will move closer to plate C and further away from plate A. As plate B moves closer to plate C the voltage from plate B to C increases at a rate of one volt per G. When a vehicle is being accelerated positively, plate B will move closer to plate A and further from plate C.
2.9.2 SKID RESISTANCE TESTS – HOLDEN OMEGA SEDAN

Table 2.1 Skid resistance tests in north bound lane north of collision scene on newly resurfaced road section

<table>
<thead>
<tr>
<th>Test</th>
<th>Time (s)</th>
<th>Speed (km/h)</th>
<th>Average G</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.41</td>
<td>38.7</td>
<td>-0.770</td>
</tr>
<tr>
<td>2</td>
<td>1.49</td>
<td>40.0</td>
<td>-0.761</td>
</tr>
</tbody>
</table>
Table 2.2 Skid resistance tests in north bound lane at initial loss of control of the bus

<table>
<thead>
<tr>
<th>Test</th>
<th>Time (s)</th>
<th>Speed (km/h)</th>
<th>Average G</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3.03</td>
<td>43.3</td>
<td>-0.403</td>
</tr>
<tr>
<td>4</td>
<td>2.70</td>
<td>41.5</td>
<td>-0.434</td>
</tr>
</tbody>
</table>

Table 2.3 Skid resistance tests straddling centre dividing line of north and south bound lanes whilst travelling north

<table>
<thead>
<tr>
<th>Test</th>
<th>Time (s)</th>
<th>Speed (km/h)</th>
<th>Average G</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.97</td>
<td>36.8</td>
<td>-0.529</td>
</tr>
<tr>
<td>6</td>
<td>1.92</td>
<td>37.2</td>
<td>-0.547</td>
</tr>
</tbody>
</table>

Table 2.4 Skid resistance tests in south bound lane whilst travelling north parallel to tests 3 - 6

<table>
<thead>
<tr>
<th>Test</th>
<th>Time (s)</th>
<th>Speed (km/h)</th>
<th>Average G</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>2.25</td>
<td>39.1</td>
<td>-0.490</td>
</tr>
<tr>
<td>8</td>
<td>2.28</td>
<td>43.7</td>
<td>-0.543</td>
</tr>
</tbody>
</table>

The tests in the Holden Omega sedan on the wet road fell at or below the lower end of the allowable risk rating adjustment zones set by Vic Roads and often below the recommended investigatory levels. The tests conducted on the newly surfaced area north of the collision location provided good results for this type of road used for high volume, high
speed traffic including heavy vehicles. When the tests were performed in the south bound lane the test vehicle rotated significantly in an anticlockwise direction coming to a stop facing 180° from the commencement of braking. The rotating was severe and as a result these tests were not repeated in the test coach for safety reasons.

2.9.2.1 SKID RESISTANCE TESTS – AUSTRAL COACH

Table. 2.5 Skid resistance tests in north bound lane north of collision scene on newly resurfaced road section

<table>
<thead>
<tr>
<th>Test</th>
<th>Time (s)</th>
<th>Speed (km/h)</th>
<th>Average G</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.14</td>
<td>20.3</td>
<td>-0.503</td>
</tr>
<tr>
<td>2</td>
<td>1.2</td>
<td>21.9</td>
<td>-0.518</td>
</tr>
</tbody>
</table>

Table. 2.6 Skid resistance tests in north bound lane at initial loss of control of the bus

<table>
<thead>
<tr>
<th>Test</th>
<th>Time (s)</th>
<th>Speed (km/h)</th>
<th>Average G</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.33</td>
<td>15.5</td>
<td>-0.329</td>
</tr>
<tr>
<td>4</td>
<td>1.68</td>
<td>19.0</td>
<td>-0.318</td>
</tr>
<tr>
<td>5</td>
<td>2.12</td>
<td>24.0</td>
<td>-0.319</td>
</tr>
</tbody>
</table>
Table 2.7 Skid resistance tests straddling centre dividing line of north and south bound lanes whilst travelling north

<table>
<thead>
<tr>
<th>Test</th>
<th>Time (s)</th>
<th>Speed (km/h)</th>
<th>Average G</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>2.00</td>
<td>23.6</td>
<td>-0.333</td>
</tr>
<tr>
<td>7</td>
<td>1.59</td>
<td>22.3</td>
<td>-0.397</td>
</tr>
</tbody>
</table>

Fig. 2.2 Friction Coefficient of large sedan and coach on Henty Highway, Heathmere

It is clearly evident, from Fig. 2 that the friction coefficient determined from the skid resistance test in the Austral Coach that all results fell well below the Vic Roads recommended levels. It must be noted however that the recommended levels are set in relation to passenger vehicles. When
comparing the results of the Holden Omega sedan with the recommended levels it is apparent that the results obtained generally fall near to or below the Vic Roads recommended levels. Major Highways in Australia carry large volumes of heavy vehicles including trucks and coaches. Consideration must be given to the reduced friction coefficient that these vehicles have in comparison to passenger vehicles.

### 2.8 OUTCOME

A full inquest into the death of Sabrina Brady, Maddison Dobie and Justin Pomery was conducted in August, October and December 2010. As a result of the inquest, Coroner Heather Spooner made a number of findings and recommendations. Coroner Spooner found that whilst the reason for the initial loss of control of the coach could not be determined the poor road surface and low friction values were responsible for this incident. She further stated that the Vic Roads system for management of risk, hazard identification, road maintenance and funding and repair were inadequate at that time. A number of recommendations were made in relation to road management. No fault lay with the coach driver, Mr Shayler. Coroner Spooner found that the deaths of Sabrina Brady,
Maddison Dobie and Justin Pomery may have been spared during the rollover had they been properly restrained.

Coroner Spooner made a number of recommendations in relation to the road management and seat belt implementation. It was recommended that Vic Roads review their road maintenance system and implement a ‘best practice’ system for inspecting, monitoring, auditing, funding and repairing road surfaces to minimize the risk of crashes. This system should also incorporate specific considerations relating to the incidence of extreme climate events and road surface management. Coroner Spooner further recommended that the Victorian Government needed to ensure that Vic Roads is adequately resourced to ensure the implementation and sustainability of the recommendations relating to road maintenance and risk. Recommendations were made that child restraints be available on all buses operating in Victoria and audible messages be played regularly during travel in an effort to increase passenger compliance. It was recommended that Transport Safety Victoria in conjunction with relevant safety agencies including Victoria Police and Vic Roads ensure that a comprehensive strategy is developed to improve seat belt compliance and passenger awareness of their importance.
As a result of the recommendations, Vic Roads has reviewed a number of existing policies in relation to their management of roads with poor surface and low surface friction. Significant changes have also been made in relation to the mandatory reporting of skid resistance issues identified by contractors during road inspections. There was previously no requirement for contractors to report to Vic Roads.

The lives of Justin Pomery, Sabrina Brady, Maddison Dobie and her unborn son, cannot be returned. It is hoped that a better understanding of road surface friction and combined efforts from Vic Roads, Victoria Government and Victoria Police to meet the recommendations by the Coroner of Victoria will significantly reduce the risk of needless loss of life due to poor road surface friction in the future.
CHAPTER 3: LITERATURE REVIEW

3.1 FRICTION

Friction is a surface force, which prevents or retards relative tangential interface motion between two surfaces or bodies studied within the field of Tribology. Tribology is a multidisciplinary field based on fluid and machine dynamics, metallurgy, physical and surface chemistry, heat transfer and stress analysis (Quinn, 1977). The specifics of a dynamic science devoted to the study of lubrication, friction and wear only evolved in 1966 when it was accepted by the Government, of the Jost Committee Report and its recommendations (Persson, 2000). Simply, tribology is the science of interacting solid surfaces in relative motion (Dowson, 1979). Whilst the term tribology is relatively new, the study of friction is far from recent. Predominantly the interest in analysis and prediction of mechanisms that occur between two surfaces in relative motion is driven by industrial sectors, which is why the new interdisciplinary approach to subjects has become necessary in recent years. Whilst not called tribology specifically, the study of the subjects has a history dating back to the turn of the 15th century.
The effects of friction on machines and materials have been the source of study and contemplation for hundreds and even thousands of years, reaching as far back as Aristotle (384-322 BC) (Dowson, 1979). Leonardo da Vinci first developed the laws of friction during the Renaissance in 1495. Leonardo formulated two basic laws of friction:

1. Friction is independent of contact area
2. Friction is proportional to load

Da Vinci never published or received credit for his work on friction for many years. In 1699, Guillaume Amontons rediscovered the two laws of friction earlier developed by da Vinci. The laws became known as Amontons Laws based on his reasoning that friction was primarily the result of work done to lift one surface over the roughness of the other, resulting in deformation and wear of the surfaces. In 1785 Charles August Coulomb refined the concepts of Amontons. Coulomb redefined the second law of friction commonly referred to as Amontons-Coulomb Law asserting that the strength due to friction is proportional to compressive force. Whilst this law holds true for many materials even today, it is not a fundamental law. Laws of Motion as devised by Sir Isaac Newton further considered friction. Newton asserted that moving friction is not dependent on speed or velocity.
This became known as the third law of friction:

3. Friction is not dependent on velocity

In recent years, Phillip Bowden and David Tabor (1950) further explored the laws of friction and determined that the true area of contact is a very small percentage of the apparent area. Bowden and Tabor determined that as the normal force increases, more asperities come into contact and the area of asperity increases. As a result, a fourth law of friction was devised:

4. Friction is dependent on the adhesive interactions between contact surfaces

Friction is a process where kinetic energy is converted into other forms of energy including heat energy, acoustic energy, optical energy, electric energy and mechanical energy. Eventually, virtually all the frictional work is converted into heat. However some of the energy is lost due to adhesion and deformation. Adhesion is attributed to only a small proportion of the loss and occurs in the thin interface zones while the great loss is due to deformation and occurs beneath the contact area in the larger volumes of material. The contact between rubbing surfaces may
have a mechanical (deformation) or atomic (adhesive) nature, although simultaneous combination of both is also possible and indeed likely (Glaeser, 2012).

Frictional phenomena, which occurs at a given moment within a nominal contact area constitutes the physicochemical characteristics of friction processes which determines the magnitude of the friction force and the type and intensity of the resultant wear. Friction is based on three mechanical interactions including the normal force, tangential force and relative velocity of the two opposing asperities. The three parameters all alter during the friction phenomenon. There are three distinguishable stages in the friction phenomenon.

1. The establishment of the micro contact between surface asperities
2. Physiochemical modifications of the micro contact and the surrounding material
3. The breaking or rupturing of the micro contact

Mechanical interactions result in a three-dimensional state of stress, which is both complex and variable. The state of stress is dependent upon the normal force, tangential force, relative velocity, the geometry of the micro
contact, and the geometry of the interacting asperities, the material properties, temperature, heat and adhesive intersections. The mechanical interactions produce elastic deformations followed by plastic deformations. Plastic deformation may produce work hardening of the material, while the frictional heat can induce recrystallisation, decrease the hardness and enhance diffusion and chemical interactions between the material and the surroundings (Persson, 2000). In addition, plastic deformations facilitate the creation of bonds between atoms and molecules and release elastic strains. Due to the complexity of the mechanical interactions, rigorous analytical assessment is essentially impossible.

In 1785 Charles Augustin Coulomb investigated the influence of five main factors, which affect friction. According to Coulomb the five main factors include:

- The nature of the materials in contact and their surface coatings
- The extent of the surface area
- The normal pressure
- The length of time that the surfaces remained in stationary contact
- Ambient conditions such as temperature, humidity and even vacuum
Coulomb was one of the first to consider the affects of tangential force on elastic fibers. In determining the friction law, Coulomb summarised many of his results using the friction law of:

\[ F = \mu L \]

Where \( F \) is the load and \( L \) is the normal force.

Coulomb surmised that the friction coefficient \( \mu \) is usually almost independent of \( L \), but also of sliding velocity so long as the velocity is not particularly high or particularly low, the contact area and the surface roughness.

In 1979, Oliver reported that tyre friction does not conform to the classical laws of friction. He identified two major components of tyre surface/friction being adhesion and hysteresis. For a dry road surface, the adhesion component dominates the friction coefficients. When a road or surface is even moderately damp, the water prevents the formation of molecular bonds and the hysteresis component is the primary source of tyre/surface friction (Oliver, 1979).
It is crucial to understand the contact mechanics of tyres whilst sliding, to critically analyse the effects of water and rainfall on the friction coefficient of car tyres and road surfaces. Heinrich (2007) performed recent research, which analyses the contact mechanics and the role of adhesion and hysteresis in rubber friction. Heinrich determined that a tyre sliding on wet roads will have a lower friction coefficient as the contribution of energy dissipation due to tread deformation, is smaller than for dry roads.

Pioneer rubber friction researcher, Grosch, has shown that in many cases rubber friction is directly related to the internal friction of rubber (Grosch, 1963). Based on the earlier work of Grosch, in 1997, Persson determined that the friction force between rubber and hard surfaces such as roads has two contributions being adhesion and hysteric components respectively (Persson, 1997). The hysteric component comes from the internal friction of the rubber. When a tyre is sliding, the asperities of the road exert oscillating forces on the rubber surface subsequently leading to cyclic deformations of the rubber and energy dissipation due to the internal damping of the rubber. The friction of a sliding vehicle tyre and road surface is also affected by adhesion. It is adhesion between the two surfaces that results in deformation of the tyre tread, which increases the friction coefficient. If the adhesive interaction between two surfaces can be reduced, then the friction force will decrease. Since adhesion is
reduced on wet surfaces, it can be concluded from the work of Persson, that the friction coefficient of car tyres and road surfaces should decrease when the road is wet. There is no discussion by Persson as to what the effect of heavy rainfall or a thick water layer in front of the tyre will have on the friction of the two surfaces in contact.

Rubber is a polymer. Most polymers exhibit a sliding friction, which is much lower than rubber. Teflon has both a static and kinetic friction, which is typically below 0.1. Based on this it can be assumed that for most polymers, the internal friction contributes less to the sliding friction than it does for rubber (Persson, 1997)

3.2 SLIDING FRICTION

W. B. Hardy studied the physics of friction at Cambridge from 1919 to 1933. Hardy claimed that friction phenomena are equally interesting for the physicist and the engineer: their investigation belongs to a most difficult field of boundary problem of physics (Blau, 2008). Factors affecting friction vary from one tribosystem to another and any modeling must be tailored to each specific circumstance. The physics of friction and its basic laws still remain elusive in many situations and simplified models
are not adequate. To accurately predict models for static or kinetic friction it is necessary to understand the dominant interfacial processes of friction and its relative stability, know the size scale at which the processes operate and identify the rules that translate the external stimulus to the response of the tribosystem. The only way to accurately model the friction coefficient of motor vehicle tyres and road surfaces is to research the two properties specifically and in relationship to each other.

The dynamics of the transition from static to kinetic friction remains mysterious although it is readily accepted that static friction varies but reaches maximum immediately before an object begins to move. Kinetic (sliding friction) is constant but a lower value than the maximum static friction. Static friction and kinetic friction are quite different.
There are a number of elementary aspects of sliding friction, which have been researched and developed by Persson (2000). The work of Persson is particularly important due to his specific research into sliding car tyres. The coefficient of friction ($\mu$) between two solid objects is determined to be the force normal to the surface ($F$) divided by the load ($L$) ($F/L$). When considering sliding friction, generally the law that states that ‘the coefficient of friction is independent of the apparent area of contact’ is obeyed. That is, when the load remains the same, the friction force will be the same no matter what the contact area. According to Persson, the coefficient of friction is usually velocity independent, unless the sliding velocity is very low due to the role of thermal activation (Persson, 2000).
supports the theory of friction of Bowden and Tabor. ‘Around 1940, Bowden and Tabor presented a simple theory for the origin of the sliding friction for clean surfaces. They assumed that the friction force is the force required to shear cold-welded junctions formed between the solids (Persson, 2000)

3.3 RUBBER FRICTION

The vital role of friction in motor vehicle collisions and collision reconstruction, and the applications of rubber tyre and road friction have assumed increasing significance over the last few decades. John Boyd Dunlop introduced the first pneumatic rubber tyre in 1888; however, it was not until 1947 that radial tyres were then fitted to motor vehicles. The introduction of radial tyres on vehicles has provoked a perpetual interest in the friction coefficient of motor vehicle tyres and paired road surfaces (Kwik-Fit, 2013). Literature specific to motor vehicle tyres is limited. Primarily tyre friction research is relevant to collision reconstruction experts and tyre manufacturers with pivotal interest in vehicle and road safety. Tyre manufacturers have a tendency to use methods and codes, which are kept confidential. Often university research is conducted in
cooperation with tyre manufacturers, again resulting in a degree of confidentiality (Steen, 2007).

Rubber products, both natural and synthetic are elastomers. Elastomers are polymeric substances that possess elasticity. A material with elasticity has no permanent deformation or dissipation. Extensive research by Brown has identified that in general, polymers do not obey the long standing Laws of Friction and the most used friction model is usually referred to as the Coulomb Model (Brown, 2006). Experiments have supported the work of Brown and often show deviations from the basic Coulomb friction model. Friction of polymers is associated with their visco-elastic behavior. The friction coefficient of polymers increases with sliding velocity until a maximum value is reached followed by a decrease of the friction coefficient. This is due to the flexibility of polymer chains (Hone, 2011). Persson (1999) reported that rubber friction differs in many ways from the frictional properties of most other solids due to the very low elastic modulus of the rubber and the high internal friction exhibited in a wide frequency region.

Rubber used in motor vehicle tyres is cross-linked polymer matrix, which typically contains only 10 per cent natural rubber (cis-1,4-polyisoprene). Most general road tyres are formed from a range of polymers including
natural and synthetic polyisoprene, poly (styrene-butadiene), polybutadiene and poly (isoprene-isobutylene) which are then blended with reinforcing fillers (Carbon black or silica), sulphur, antioxidants and processing oils (Hone, 2011). The reinforcing fillers like carbon black or silica produces two additional effects, the Payne effect and the Mullins Effect both of which are softening effects (Steen, 2007).

Friction of rubber is a complex phenomenon comprising two parts, adhesive friction and hysteresis friction. When a rubber tyre slides on a road surface, molecular bonds between the surfaces are repeatedly broken and reformed. This is adhesive friction. The dynamic deformation of the rubber as energy is lost during sliding is hysteresis friction (Brown, 2006). The hysteric friction component results from the internal friction of the rubber. Rubber tyre and road surface friction is dependent upon both the coarseness of the road surface and the viscoelastic properties of the tyre rubber. The constitutive laws for large strains cannot be applied to the stress-strain relative to rubber since rubber does not follow reversible stress-strain relations. When rubber is dynamically stretched and released the returned energy is less than the energy that is put into the rubber (Brown, 2006).
According to Persson, rubber friction differs in many ways from the frictional properties of most other solids due to the very low elastic modulus of rubber and the high internal friction exhibited by the rubber in a wide frequency region (Persson, 1998). When an elastomer slides across another surface, true sliding at the interface will not always occur. Waves of detachment traverse the interface and relative displacement will occur where contact is temporarily lost. Briggs and Briscoe identified that these waves are called Schallamach waves and resemble macro-dislocations where energy is dissipated by peeling the contact apart as the wave propagates (Briggs, Briscoe, 1978).

Research into rubber friction changed in 1971 when Schallamach observed that when rubber moves over a hard surface, true sliding does not occur. Schallamach determined that the contact area is crossed by waves of detachment and it is only in this area that contact is lost and that relative motion between the two surfaces continues to occur.

Schallamach was one of the first researchers to seriously study rubber friction recognising that in relation to friction, rubber does not act in a way similar to other compositions such as metals, which form the basis for Amontons and Coulomb’s Laws. According to Rand and Crosby, Schallamach waves are a dominant mechanism in the friction of soft
material interfaces. Schallamach waves are essentially air tunnels, which provide relative displacement between a sliding material and the substrate (Rand, Crosby, 2006). For Schallamach waves to form, it is necessary that adhesive forces at the interface have enough strength to prevent movement at the rear of the interface that subsequently creates a zone of tension. The interface will then begin to shear which causes compression in the front of the contact area. Critical compressive stress prior to slip will result in buckling of elastomers. If the adhesion energy that resists interfacial separation is greater than the stored elastic energy which causes buckle compression then the buckle will attach to a slider and subsequently form a wave providing displacement between the substrate and the slider. There are three critical aspects relative to Schallamach’s wave phenomenon:

1. how the waves form
2. the interfacial stress required to propagate them
3. their regime of existence

Briggs and Briscoe took the work of Schallamach further. Schallamach developed the theory of Schallamach waves from models of rubber and smooth surfaces such as glass. Briggs and Briscoe then went on to consider the effects a rough surface had on waves of detachment. Their
work determined that waves of detachment are also present when the surface is rough and therefore the same explanation of friction force that applies to smooth surfaces remains relevant. It is well established that when rubber slides over smooth and rough surfaces the frictional force is accounted for in terms of net work required to peel rubber away from the surface and then re adhere to it (Briggs, Briscoe, 1976). It is clear that during sliding the viscoelastic deformations of rubber induced by the adhesional interaction with the substrate, increase the friction force. Therefore, if the adhesional interaction between a substrate and rubber can be reduced, then friction force will decrease. Persson (1999) states that if rubber is slid on a substrate covered by a thin layer of water, then sliding friction is reduced. This is because water is trapped in the surface cavities of the substrate thereby leading to reduce viscoelastic deformations of the rubber.

Briggs and Briscoe also established that adhesion of rubber depends markedly on the roughness of the surface with which it is in contact. Road/Tyre friction is a function of tread depth, water depth and velocity.
3.4 ROAD SURFACE TEXTURE

Road surface/tyre friction is the result of the interaction between both the tyre and the road surface and is not a property of the tyre or the road surface individually. Tyre/Road surface friction is dominated by the texture of the road surface. Different road surface textures make different contributions. As discussed, skid resistance depends on the chemical bonding between the road stones and the tyre rubber (adhesion) and the deformation and recovery of the tyre as it passes over the projections and depressions in the road surface (hysteresis). When water is present between the road and tyre, chemical bonding is affected. In wet conditions, the ability for chemical bonding to occur depends on the micro texture.

3.5 FACTORS AFFECTING FRICTION

3.5.1 VELOCITY

In 1780, Coulomb identified a difference between static and dynamic friction coefficients. As a result of his work he determined that the friction coefficient is independent of sliding speed (Schallamach, 1952). A number
of researchers have demonstrated that instantaneous tyre/road friction decreases non-linearly with increasing speed (Takadoum, 2007). Shah and Henry identified that the most significant decrease in friction will occur at vehicle speeds up to 30 km/h and then become more gradual as the speeds continue to increase (Heinrichs, Lloyd, Allin, 2004). In 2002, Heinrichs identified that the road/tyre friction coefficient was lower at 20 km/h compared to 40 km/h (Shah, Henry, 1978). Laws established by Coulomb were substantiated mostly with metals. More recent research has shown that highly elastic materials such as rubber don’t agree with theoretical predictions relating to velocity. Although researchers generally agree that tyre/road friction is affected by velocity, there is conflict in relation to where maximum and minimum speed thresholds occur when considering tyre/road friction specifically.

3.5.2 TEMPERATURE

There is no general macroscopic theory of friction, which allows the prediction of the friction coefficient of two materials, since it is the nature of the two surfaces in contact, which has the greatest influence on the result (Butt, Kappl, 2010). According to Coulombs ‘Laws of Friction’ the coefficient of friction is independent of temperature (Wada, Uchiyama, 1993). However, this theory has since been challenged with evidence that
the coefficient of friction between pure metals is independent of temperature while viscoelastic properties of rubber like materials are strongly temperature dependent. Polymers do not obey Coulombs Laws (Schallamach, 1952). The ‘William Landel Ferry Theory’ identifies that rubber friction is essentially a viscoelastic phenomenon and very sensitive to temperature (Takadoum, 2007). Research theories relating to the effects of temperature on friction coefficient increases as temperature increases, until the surface reaches maximum softening at which point the friction coefficient will begin to decrease (Wrobel, Szymiczek, 2008). Investigation into the effects of flash temperature on the friction coefficient of a rubber block sliding on a rough surface concluded that as localized temperature of rubber increases the friction coefficient decreases (Persson, 2006). The research did not consider the temperature of the rubber block. It only considered the temperature of the surface upon which the rubber block was sliding. Accordingly this research may not be relevant to the research proposed.

3.5.3 LUBRICATION

The mechanism of traction under dry conditions involves a complex interlocking between road surface texture and dynamic rubber properties
Dry friction describes the reaction between two solid bodies in contact with each other when they are in motion and when they are not (Flintsch, McGhee, Izeppi, Najafi, 2012).

Lubricants will lower friction and reduce wear between two sliding solid bodies. Persson (1999) determined that a lubricant is used to lower the friction and reduce wear between two sliding bodies. Most surfaces will be covered with a layer of oil. Roads are certainly no exception. These oils will act as a lubricant and will lower the friction coefficient between car tyres and road surfaces but these oils are present on both dry and wet surfaces. Grease and oil are better lubricants than water as oil has a much higher viscosity. Fluid with a higher viscosity will reduce friction coefficient. If the depth of lubrication is sufficient to fully separate the two surfaces in contact then the frictional interaction can be effectively modeled using lubrication theories. If despite lubrication, the solid bodies remained in contact then the characteristics of the bodies, the surface structure and any third bodies play a role.

‘The single most important factor affecting tyre friction force in practice is the presence of water in various forms including water, snow and ice. In most temperature climates on modern roads it has been shown that during a range of rainfall intensities normally encountered, the water rarely
exceeds 2mm and is typically 1mm or less.’ (Mooney, Wood, 1996). Experiments have shown that road/tyre friction in low water depth conditions is a complex interaction between the road surfaces, tyre construction and tread depth.

The depth of water on the road greatly influences tyre/road friction (Claeys, Alvarez, Horowitz, Canudas, Richard, 2001). There is a distinction between the effects of thin water layers (less than 0.7 mm) in comparison to thick water layers (more than 1.1 mm). When there is a thin layer of water only, the contact between the tyre and road is completely lost due to full contamination of the interface – viscous hydroplaning. When the layer of water becomes thick, extra force is generated in front of the tyre due to the accumulation of water providing hydrodynamic forces. The water layer depth determines the magnitude of the force. It is important to be aware that once the tyre rises to the top of the water surface then hydroplaning occurs and the friction force provided by the pushing of water is lost and friction force is subsequently reduced.

Rubber friction on wet rough substrates at low velocities is typically 20% to 30% smaller than for the corresponding dry surfaces (Persson, Tartaglino, Albohr, 2004). Persson has conducted extensive studies on sliding friction and suggests that rubber friction on wet road surfaces cannot be
explained by a hydrodynamic effect but rather suggests that water pools within the road aggregate. As the rubber tyre passes over the surface, the water is trapped within the aggregate fissure forming pools and creating a smoother surface and subsequently a lower friction coefficient. No matter what the reason, it is accepted strongly by tribologists and engineers that wet friction is typically lower than dry friction when comparing the same surfaces. Research conducted by both Persson and Schallamach does not perform rubber/road friction testing on deep water pooling above the level of the aggregate.

According to Moore (1967) at speeds up to 60 km/h flooded roads consistently give higher sliding friction values. It was his belief that whilst there was evidence that this consistently occurs there is no satisfactory explanation or theory for the phenomenon. Further investigations identified that wet rear tyre friction coefficient is similar to the dry friction value but the front tyre traction is substantially below the dry value. The dry values have more variability that the wet results. This is most likely because the dry values represent variations associated with local differences in surface texture, whereas the presence of water in the wet tests appears to minimize texture variations (Metz, 2006).
Persson (1999) considered both the relevance of lubricant viscosity and depth when researching sliding friction. According to Persson when two layers separated by a layer of fluid are pushed together then the fluid will be pushed out. The higher the liquid viscosity, the longer this process will take. If viscosity of the separating fluid is low enough then the fluid will be squeezed out rapidly leading to direct contact between the two surfaces. This is boundary lubrication and typically results in a very high sliding friction, which is independent of speed. Rainwater has a low viscosity.

Friction coefficient on a wet road decreases with increasing vehicle speed. At low travel speeds, road micro texture is the primary contributor to friction coefficient. Macro texture and water depth influence the extent to which friction decreases with increasing speed (McLean, Foley, 1998). Micro texture is asperities within a road surface where the individual pieces of aggregate are less than 0.5 mm. Macro texture is measured as a texture depth and relates to the larger aggregate over 0.5 mm.
3.6 HYDROPLANING

True contact between a vehicle tyre and a road surface is established only at the rear of the nominal contact length. The front region of the contact length works to displace any fluid forward of the tyre. As the amount of fluid to be displaced increases the percentage of nominal contact area reduces until it becomes zero at which time hydroplaning is said to be occurring. That is the friction is almost zero and there is not ability to steer or brake the vehicle. The vehicle is essentially on top of the water with a complete layer of water between the tyre and the road. ‘On a wet road surface, elastohydrodynamic effects attempt to entrain fluid across the individual asperities of the road texture thereby destroying intimate tread to surface contact and rapidly promoting the onset of the hydroplaning phenomenon’ (Moore, 1967). The mechanism of hydroplaning is characterized by a rapid spread of interfacial film of liquid from both ends of the contact length towards the centre. When hydroplaning occurs, the adhesion contribution to friction has been lost and the hysteresis contribution is negligibly small. Hydroplaning does not occur instantaneously but it occurs rapidly and seemingly suddenly to a vehicle driver.
3.7 FRICTION AND COLLISION RECONSTRUCTION

In Australia, the annual cost of motor vehicle collisions totals more than $17 billion dollars. While that figure alone is astounding, it doesn't recognise the emotional cost to those left grieving the fatally injured or those caring for the 25,000 who are seriously injured each year (Risby, Cregan, De Silva, 2010). No monetary figure can be put on the real cost of collisions in this country.

There are two methods used to estimate the cost of an accident: one economic and the other is comprehensive. Economic costs are a measure of the productivity lost and expenses incurred because of accidents. Comprehensive costs not only include the economic costs but also measure the value of lost quality of life associated with the deaths and injuries, that is, what is society prepared to pay to prevent them? Comprehensive costs are greater than economic costs.

Valuation of road crash costs involves an estimation of the total number of crashes and injuries, then quantifying the cost of specific crash components. There are human costs including loss of life, treatment of injuries and ongoing care of persons with disability, vehicle damage costs and general costs including insurance administration and emergency
services cost. According to the Bureau of Infrastructure, Transport and Regional Economics each fatality costs $2.4 million, each hospitalization injury costs $214,000 and each non-hospitalisation injury costs around $2100.00 (Risby, Cregan, De Silva, 2010).

In road fatalities and collisions the term collision or crash is typically used rather than accident as generally vehicle collisions are avoidable and not the result of chance.

Collision reconstruction is the practice of determining the movement, relative positions and interaction of motor vehicles pre, post and during a collision event. After critical assessment of the human, environmental and vehicle factors available at a collision scene, a collision reconstructionist will use scientific and physics principles to determine how and why a collision has occurred, potentially also assigning liability.

The determination of the friction coefficient of a road-tyre surface is critical in most aspects of motor vehicle collision reconstruction. According to Warner, Smith, James and Germane (1983) tyre-road friction values are highly dependent on numerous physical factors including tyre design, side force limitations, road surface wetness, vehicle speed and load shifting.
It is the application of Coulomb's friction law

\[ F = \mu L \text{ where } L = Mg \text{ (vehicle weight)} \]

This allows the minimum speed of a vehicle to be determined from the length of a skid. This is a critical factor in collision reconstruction. The application relies upon the skid distance \( d \) being obtained and by the condition that the initial kinetic energy \( \frac{Mv^2}{2} \) is completely dissipated by the friction between the road and the vehicle tyres during the skid.
CHAPTER 4

VEHICLE VELOCITY AND ITS EFFECT ON FRICTION

4.1 INTRODUCTION

Estimation of the friction coefficient of vehicle tyres and paired road surfaces is necessary to determine pre and post impact vehicle velocities in motor vehicle collision reconstruction. Average friction values may be assumed for a range of surfaces based on previous research. Alternatively, accelerometers can provide more accurate values when used in testing conducted at the relevant collision site.

Accelerometers require brake tests to be performed in test vehicles. Tests are usually performed at velocities determined to be safe for the conditions, often well below the velocities of vehicles being analysed. The use of the friction coefficient values obtained using accelerometers, assumes that the deceleration rate is independent of vehicle velocities.

Amontons' law of friction, which holds true for many material combinations, is not obeyed by elastomers such as rubber. Average tyre/road friction coefficients have been shown to be dependent on vehicle
velocities by a number of researchers (Heinrichs 2004, Shah 1978, Leu 1978, Gunaratne 2000). Therefore, the primary objective of this study is to experimentally determine the effects of vehicle velocities on the friction coefficient with and without ABS. Tests using actual vehicles not fitted with antilock braking systems (ABS) at a range of velocities from 20 km/h to 80 km/h identified that as velocity increased, friction decreased non-linearly. The most substantial decrease in friction coefficient results occurred in vehicles travelling up to 30 km/h with little significance in friction coefficient values recorded for vehicles travelling 60 km/h to 80 km/h (Heinrichs, 2004). ABS will not work if the vehicle velocity is below 25 km/h (Wu, 2010) Consequently comparison testing with and without ABS can only occur upwards of 30 km/h.

Friction coefficient ($\mu$) is the maximum value of the frictional force divided by the normal force. An accelerometer calculates the friction coefficient 100 times per second from the commencement of braking, producing one average result. From the commencement of braking, friction coefficient increases until it reaches peak immediately prior to wheel lock up when it then begins to decrease along the skid length. A vehicle travelling faster will produce a longer skid and subsequently a lower deceleration rate.

When emergency braking is applied to a vehicle, the peak friction coefficient is attained immediately before wheel lock. When a vehicle is
fitted with ABS, the pressure on the hydraulics will reduce as the wheels begin to lock, aimed at keeping the friction coefficient near to peak. This will continue to occur up to 15 times per second and is designed to increase braking efficiency and reduce the risk of vehicle loss of control (Erjavec, 2003). The friction coefficient of a vehicle under ABS braking is higher than a vehicle without ABS.

Study of friction relating to viscoelastic properties such as rubber is very new and research is limited in this area. The additional consideration of ABS further reduces the extent of research due to this introduction being only recent. It is generally suggested in the literature that dry sliding frictional force of a tyre decreases with increasing sliding velocity (Chowdury, 2003) however there is some data that contradicts this. It is critical that friction coefficient of viscoelastic properties such as vehicle tyres be determined specifically. In 2004, Cross considered the effect of velocity on the friction coefficient of an elastically soft material of tennis ball cloth sliding on smooth surfaces. He determined that sliding friction increases with velocity for the elastic material. Whilst vehicle tyres have elastic properties there is a stick-slip phenomenon caused when skidding. According to Cross this will result in a decrease in friction coefficient with an increase in velocity contradicting other elastic and metal materials. The decrease in friction coefficient sometimes referred to as the velocity decrement of sliding friction, has a relatively small effect for low and
moderate highway velocities (Warner, 1983). Limpert (1978) suggests that the variation in friction coefficient due to velocity is between 0.0017 and 0.005 mph^{-1}.

The objectives of this study were to identify how vehicle velocity affects the tyre/road friction coefficient on dry asphalt roads using vehicles with and without ABS. We believed that as pre skid vehicle velocity increases, the tyre/road friction coefficient on dry bitumen would decrease in vehicles without ABS and increase in vehicles with ABS. The results of this study will increase the accuracy of vehicle velocity estimates in collision reconstruction for vehicles both with and without ABS, over a range of velocity. Will friction coefficient remain the same as velocity is increased? Is this the same for vehicles with and without ABS? This research will provide collision investigators and reconstruction experts worldwide, a better understanding of the effects vehicle velocity on the friction coefficient of the car tyres and road surfaces specifically when ascertaining the road/tyre friction coefficient of a collision scene using a vehicle travelling at a velocity considerably less than the subject vehicle.
4.2 EXPERIMENTAL CONDITIONS

All preliminary ABS and non ABS tests were conducted on 16\textsuperscript{th} June 2011 between 3:03 pm and 3:56 pm. The road was dry and conditions were clear. No rain had been recorded in the 7 days prior. The ambient temperature was recorded at 13\textdegree{}C (55\textdegree{}F), which remained constant throughout the test period. Light winds only of less than 10 km/h were observed.

4.2.1 LOCATION

Tests were performed in the service lane on the west side of Dorset Road, Bayswater, Victoria, Australia between Allambanan Drive and Huntingdon Avenue. All tests were performed whilst travelling in a northerly direction. The geographic latitude, longitude and elevation are: -37\textdegree{}49’41.49”, +145\textdegree{}17’14.90”. The service lane is privately owned and not open to the public. The road is not used as a thoroughfare and was developed in preparation for future industrial developments to the west. The road falls under the Roads Corporation Victoria jurisdiction and has not been resurfaced since 2003. The road is in excellent condition due to very low
levels of vehicle traffic and essentially mild environmental conditions including temperature and rainfall. The area is well drained. The service road in the direction of testing is shown in Fig. 4.1. The service lane aggregate is depicted in Fig. 4.2
4.2.2 TEST VEHICLE

Tests were conducted in an Australian built 2010 General Motors Holden (GMH) Commodore Omega four door sedan. The 3.0 litre V6, spark ignition direct injection vehicle was fitted with a six velocity automatic transmission. Ventilated disc brakes were fitted to both the front and rear. Rear wheel drive, the vehicle had antilock braking system (ABS) fitted as standard. The ABS was disengaged for non-ABS tests. No performance modifications had been made to the vehicle with all braking, steering and
suspension components fitted by the manufacturer as standard. The vehicle's tested mass with two occupants, was 1762 kg. The vehicle had travelled 21,091 km from new at the commencement of the first test. The brakes were operating effectively and efficiently having been replaced at 15,000 km. The vehicle was serviced at 20,000 and required no brake adjustment or replacement. The vehicle type used in this study is depicted in Fig. 4.3

Fig 4.3 2010 Holden Omega sedan using for preliminary and verification testing
4.2.3 TYRES

The vehicle was fitted with four Bridgestone Turanza ER3HZ tyres, which were fitted to the vehicle at new. The 225/60 R16 tubeless steel belted radial tyres are considered to be a mid-range touring model by the manufacturer. The minimum tyre tread depth on any tyre was 4mm and all tyres were inflated to 34 PSI (2.3 x 10⁵ Pa) prior to the commencement of testing. The tyres have been used for both country and city driving and no damage had been recorded or repairs carried out prior to the tests. Visual inspection showed no evidence of uneven wearing of the tyres. Tread pattern of Turanza ER3HZ tyre shown in Fig 4.4

Fig 4.4 Tread pattern of Bridgestone Turanza ER3HZ tyre
4.2.4 BRAKE TEST COMPUTER

The VC4000 Vericom brake test system was used on this experiment. The device has 3 major components: a crystal clock, an accelerometer and a microcontroller which measures the instantaneous G-force 100 times per second and can measure the difference between ABS and standard brakes. The VC4000 is activated at a 0.2 g threshold upon initiation of the brake pedal load cell. The device is attached to the windscreen of the test vehicle and is considered one of the most modern and reliable test devices to determine g-force. The g-force is measured within 0.001 g providing accuracy of 1%. Distance is recorded at an accuracy of 1% over 400 m and velocity is accurate within 1% up to 100 kmh. Therefore the g-force will not change unless the velocity changes. Vericom Brake Test Computer shown in Fig. 4.5
4.2.5 TEST VELOCITY

The series of skid tests, at a range of velocities were performed in one vehicle. The friction coefficient of the vehicle tyres and the road surface upon which it was travelling was determined during the tests. Tests were performed at 30 km/h, 40 km/h, 50 km/h, 60 km/h and 80 km/h. A passenger vehicle registered for general use on a true road with a human driver (author) was used for all tests.
4.3 METHODOLOGY

The test vehicle containing two adults (driver and observer/recorder) was driven in a northerly direction along Allambanan Drive, Bayswater. Once the vehicle test velocity was attained, the foot brake was activated with maximum pressure. Pressure remained 100% until the vehicle came to a complete stop and the results were displayed on the Vericom brake testing computer display screen. The first series of tests were performed with the ABS on. The lowest velocity tests were conducted first, that is two tests at 30 km/h were performed then the velocity was increased in 10 km/h increments to 40 km/h and two tests were again performed with continual velocity increases up to 80 km/h. At the completion of the ABS testing, removing the ABS fuse disabled the ABS and the series was again repeated commencing at 30 km/h and increasing up to 80 km/h. Testing position on the roadway remained in the same general area but was gradually brought forward to prevent skids being consistently performed over the top of each other.
4.4 RESULTS

4.4.1 ANTILOCK BRAKING SYSTEM (ABS) ENABLED

When the vehicle, travelling at 35.6 km/h and 32.8 km/h, was skidded with the antilock braking system enabled, the deceleration rate was calculated at -0.885 g and -0.930 g (Table 4.1). Deceleration experienced by an object is due to the vector sum of non-gravitational forces acting on an object free to slow. The accelerations that are not produced by gravity are termed proper acceleration and it is only these that are measured in g-force units. When the tyres of a vehicle are locked and sliding, the deceleration of the vehicle is due wholly to the friction coefficient of the car tyres and road surfaces. By determining the g-force of a slowing vehicle we know the friction coefficient. The mean of the two results was -0.907 g.

At 42.6 km/h and 41.9 km/h, the deceleration rate was calculated at -0.895 g and -0.893 g. The mean deceleration rate was -0.894 g showing a decrease of -0.013 g (1.44%) as the vehicle velocity increased. At 54.3, 52.9 km/h and 52.8 km/h, the deceleration rate of the skidding vehicle with ABS enabled was calculated at -0.889, -0.948 g and -0.953 g. The mean friction coefficient was -0.930 g. The mean deceleration rate increased by -0.036g, from the lower vehicle travelling velocity at 42.2 km/h. In the vehicle that was skidded whilst the ABS was enabled, the deceleration
rate increased as the vehicle velocity increased from 42.2 km/h to 83.1 km/h by -0.061g (6.4%) as shown in Table 1. The lowest deceleration rate was recorded at the tests conducted at 41.9 km/h. The highest deceleration rate was recorded on the test conducted at 64.4 km/h. The test conducted at 32.8 km/h recorded a higher friction coefficient than the test conducted at 41.9 km/h.

Table 4.1. deceleration rate of a Vehicle Sliding on Bitumen with Antilock Braking System (ABS) enabled

<table>
<thead>
<tr>
<th>VELOCITY (km/h)</th>
<th>TIME (sec)</th>
<th>DISTANCE (m)</th>
<th>AVERAGE G (g)</th>
<th>MEAN G (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35.6</td>
<td>1.14</td>
<td>6.10</td>
<td>-0.885</td>
<td>-0.907</td>
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<tr>
<td>32.8</td>
<td>1.00</td>
<td>5.00</td>
<td>-0.930</td>
<td></td>
</tr>
<tr>
<td>42.6</td>
<td>1.35</td>
<td>8.80</td>
<td>-0.895</td>
<td>-0.894</td>
</tr>
<tr>
<td>41.9</td>
<td>1.33</td>
<td>8.40</td>
<td>-0.893</td>
<td></td>
</tr>
<tr>
<td>54.3</td>
<td>1.70</td>
<td>13.70</td>
<td>-0.889</td>
<td>-0.930</td>
</tr>
<tr>
<td>52.9</td>
<td>1.58</td>
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<td></td>
</tr>
<tr>
<td>52.8</td>
<td>1.57</td>
<td>12.30</td>
<td>-0.953</td>
<td></td>
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<tr>
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<td>-0.958</td>
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</tr>
<tr>
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<td>2.30</td>
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<td>2.40</td>
<td>29.7</td>
<td>-0.956</td>
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</tbody>
</table>
Fig. 4.6 deceleration rate of a Vehicle Sliding on Bitumen with Antilock Braking System (ABS) enabled
4.4.2 ANTILOCK BRAKING SYSTEM (ABS) DISABLED

With the ABS disabled, the vehicle was skidded at 34.3 and 34.4 km/h. The deceleration rate was calculated at -0.852 g and -0.834 g. When the vehicle velocity was increased to 42.2 km/h and 42.4 km/h, the deceleration rate was calculated at -0.861 g and -0.834 g. The deceleration rate increased by -0.004 g as the vehicle velocity was increased. When the vehicle velocity was further increased to 52.8 km/h and 52.9 km/h, with the ABS disabled, the deceleration rate was calculated to be -0.840 g and -0.823 g. As the velocity increased from 42 km/h to 52 km/h the mean deceleration rate decreased by -0.063 g (1.89%). As the velocity further increased from 42.2 to 81.4 km/h the deceleration rate decreased by -0.070 (8.3%) (see Table 2). The highest deceleration rate was recorded in the tests conducted at 42.4 km/h. The lowest deceleration rate was recorded on the test conducted at 81.4 km/h. The test conducted at 34.3 km/h recorded a higher friction coefficient than the test conducted at 42.4 km/h (Table 4.2).
Table 4.2  Deceleration rate of a Vehicle Sliding on Bitumen with Antilock Braking System (ABS) disabled

<table>
<thead>
<tr>
<th>VELOCITY (km/h)</th>
<th>TIME (sec)</th>
<th>DISTANCE (m)</th>
<th>AVERAGE G (g)</th>
<th>MEAN G (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34.3</td>
<td>1.14</td>
<td>5.9</td>
<td>-0.852</td>
<td>-0.843</td>
</tr>
<tr>
<td>34.4</td>
<td>1.17</td>
<td>5.9</td>
<td>-0.834</td>
<td></td>
</tr>
<tr>
<td>42.2</td>
<td>1.39</td>
<td>8.5</td>
<td>-0.861</td>
<td>-0.847</td>
</tr>
<tr>
<td>42.4</td>
<td>1.44</td>
<td>8.7</td>
<td>-0.834</td>
<td></td>
</tr>
<tr>
<td>52.8</td>
<td>1.78</td>
<td>13.2</td>
<td>-0.840</td>
<td>-0.831</td>
</tr>
<tr>
<td>52.9</td>
<td>1.82</td>
<td>13.7</td>
<td>-0.823</td>
<td></td>
</tr>
<tr>
<td>61.6</td>
<td>2.23</td>
<td>18.9</td>
<td>-0.782</td>
<td>-0.802</td>
</tr>
<tr>
<td>61.5</td>
<td>2.12</td>
<td>18.0</td>
<td>-0.822</td>
<td></td>
</tr>
<tr>
<td>81.4</td>
<td>2.93</td>
<td>32.5</td>
<td>-0.787</td>
<td>-0.777</td>
</tr>
<tr>
<td>81.4</td>
<td>3.00</td>
<td>33.5</td>
<td>-0.786</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 4.7 deceleration rate of a Vehicle Sliding on Bitumen with Antilock Braking System (ABS) disable
COMPARISON

**Fig. 4.8** Comparison of the deceleration rate of a vehicle sliding on bitumen with and without ABS between 40 km/h and 80 km/h
4.5 DISCUSSION

The velocity of a vehicle at the commencement of sliding will affect the friction coefficient of the vehicle tyres and the road surfaces upon which it is travelling. As the velocity of the vehicle at commencement of skidding increased, the friction coefficient decreased when the vehicle ABS was disabled and increased when the vehicle ABS was enabled. However, this only occurred above 40 km/h. Below 40 km/h the friction coefficient increased as velocity increased for vehicles without ABS and decreased as velocity increased for vehicle without ABS.

At 40 km/h, the difference in friction coefficient between a vehicle with and without ABS was -0.047g. The friction coefficient remained higher in the vehicle with the ABS enabled at 40 km/h although the total stopping distance was equal in both vehicles. At 80 km/h, the difference in the friction coefficient in the vehicle with and without ABS was -0.178 g and the average stopping distance of 4.5 metres in the vehicle without ABS. The effectiveness of ABS increases as velocity increases above 40 km/h.

These on road tests did not harmonise with the earlier research of Heinrich (1978) in relation to non ABS friction coefficient at lower velocities. Heinrich et al. identified that as velocity increased, friction decreased non-
linearly with the most substantial decrease in vehicles travelling up to 30 km/h. The most substantial decrease in these results occurred between 50 km/h and 60 km/h with an increase observed between 20 km/h and 30 km/h.

Both series of tests support a peak at 40 km/h. With ABS enabled, the lowest friction coefficient between the vehicle tyres and the road surface was observed at 40 km/h. With the ABS disabled the highest friction coefficient between the vehicle tyres and the friction coefficient was observed at 40 km/h. It is not possible to determine whether the friction coefficient peaks or plateaus at 70 km/h – 80 km/h with the ABS enabled and disabled. Further tests need to be conducted at 70 km/h, 80km/h, 90 km/h and 100 km/h to determine what trend occurs above 60 km/h.

There were only two tests that could be considered to be statistically significant. The test at 81.4 km/h and the test at 42.2 km/h when the ABS was off were the only results to fall within the 95% confidence interval range. Of the 11 tests performed with the ABS enabled, 8 fall within the 75% confidence range. With the ABS disabled, only half of the tests provided results that fell within the 75% confidence range.
\[ Vi = \sqrt{Ve^2 - 2ad} \]

Where

\( Vi \) = Initial velocity

\( Ve \) = End velocity

\( a \) = acceleration (average g x 9.81)

\( d \) = distance

Using the total braking distance of 33.5 metres it is possible to determine the effect of using an average g determined from a vehicle travelling at 40 km/h when the vehicle was travelling at a velocity above 80 km/h.

Friction Coefficient determined at 40 km/h:

Equation 1:

\[ Vi = \sqrt{0^2 - (2 \times 9.81 \times -0.834 \times 33.5)} \]

\[ Vi = 84.27 \text{ km/h} \]

Friction Coefficient determined at 80 km/h:

\[ Vi = \sqrt{0^2 - (2 \times 9.81 \times -0.768 \times 33.5)} \]

\[ Vi = 80.89 \text{ km/h} \]
The Vericom brake test computers record the distance of braking using a multi controller. This records braking distance from when the first application of braking is made by the driver. There is a delay between initial brake application and tyre lock up. Tyre skid marks are rarely visible immediately upon tyre lock up. Test 10 with ABS disabled recorded a total braking distance of 33.5 metres however physical measurements taken from the skid marks on the road were 29.1 metres.

Using the total braking distance of 29.1 metres it is possible to determine the effect of using an average g determined from a vehicle travelling at 40 km/h when the vehicle was travelling at a velocity above 80 km/h.

Friction Coefficient determined at 40 km/h:

\[ Vi = \sqrt{0^2 - (2 \times 9.81 \times -0.847 \times 29.1)} \]

\[ Vi = 79.16 \text{ km/h} \]

Friction Coefficient determined at 80 km/h:

\[ Vi = \sqrt{0^2 - (2 \times 9.81 \times -0.777 \times 29.1)} \]

\[ Vi = 75.82 \text{ km/h} \]
When using the physical marks left by a skidding vehicle, (the evidence most readily available to collision investigators) rather than the total braking distance (calculated using a multi controller), an underestimate of the vehicle travelling velocity will be made irrespective of what velocity the test vehicle was travelling to obtain the friction coefficient. All formulas for determining velocity that take into account braking distance were developed in reference to the total braking distance. Collision investigators can only rely upon the available physical evidence of braking such as skid marks which will be somewhat less that the total braking distance.

While not considered statistically significant, the trend observed in the friction coefficient as velocity increases is well defined. The results are significant in relation to collision reconstruction. Based on the tests performed and the data obtained, the relevance of the friction coefficient and its effect on vehicle velocity analysis can be identified. The highest friction coefficient result with the ABS disabled was recorded at the test performed at 42.2 km/h with an deceleration rate of -0.861g. This result is below the lowest deceleration rate obtained when the ABS was enabled. This result was obtained in a test performed at 35.6 km/h. From this it can be determined that any friction coefficient that is determined using a vehicle without ABS or a vehicle which has ABS which is disabled will
provide a value which is below the true velocity for a vehicle with ABS. Using a friction coefficient obtained in a vehicle without ABS will result in an underestimate of the skidded vehicle velocity with ABS on.

The velocity at which friction tests are conducted to determine tyre/road friction coefficients is a relevant consideration up to 80 km/h. As vehicle velocity increases, the significance of the results decreases. When friction coefficient tests are conducted in a vehicle without ABS to determine the velocity of a vehicle that does not have ABS, it is important to be aware that tests conducted below the velocity of the vehicle being analysed may result in an overestimate of vehicle velocity if using the total braking distance. Using the tests conducted without ABS, the mean deceleration rate results at 34 km/h, would result in an overestimate of velocity in the vehicle travelling at 81 km/h. Using the mean deceleration rate obtained at 81.4 km/h provides a velocity estimate result of 81.3 km/h. All mean deceleration rate results at 30 km/h, 40 km/h, 50 km/h and 60 km/h without ABS, produce velocity overestimates of up to 4.0 km/h above the actual velocity of a vehicle which is travelling faster than that friction test vehicle velocity, at the commencement of braking. By neglecting pre skid braking interval, the pre braking vehicle velocity is underestimated by 5-15%. If using skid length only, then the velocity at which the friction coefficient
testing occurs is irrelevant up to 80 km/h and will still provide an underestimate of the true vehicle velocity pre braking.

Using a regression model it is possible to adjust measured friction coefficient values to account for the difference in vehicle velocity between the test vehicle velocity and the assessed vehicle velocity in vehicles without ABS. The MEHEGAN prediction model was developed to facilitate the ability to predict friction whilst accounting for a difference in vehicle velocity.

\[ R^2 = 0.964 \]
\[ R = 0.982 \]
To determine the friction coefficient at 81.4 km/h using the friction coefficient recorded at 42.3 km/h using the MEHEGAN prediction model:

**Equation 2. MEHEGAN prediction model:**

\[
\mu_p = -0.982 \frac{n-m}{10} \times \mu^m
\]

\[
\mu_p = -0.982^{3.91} \times -0.847
\]

\[
\mu_p = -0.788
\]

Where \( n \) = the velocity at which the test was performed and \( m \) = the velocity the friction is being predicted for. Vehicle velocity determined using the MEHEGAN prediction model friction coefficient based upon braking distance of 32.5 m as obtained in tests performed at 81.4 km/h.

\[
V_i = \sqrt{V e^2 - 2ad}
\]

\[
V_i = \sqrt{0^2 - (2 \times 9.81 \times -0.788 \times 32.5)}
\]

Velocity = 80.69 km/h (underestimate by 0.71 km/h)
Vehicle velocity determined using the MEHEGAN prediction model friction coefficient obtained at 42.3 km/h based upon braking distance of 32.5 m obtained in tests performed at 81.4 km/h

\[ V_i = \sqrt{0^2 - (2 \times 9.81 \times -0.847 \times 32.5)} \]

Velocity = 83.66 km/h (overestimate by 2.26 km/h)

Using the adjusted friction coefficient the vehicle velocity calculated was less than 1.0 km/h under the true velocity of the vehicle. When using the friction coefficient determined at 42.3 km/h the calculated velocity overestimated the true velocity by 2.26 km/h. It should be noted that the calculations were based on the braking distance during testing not on the physical evidence of braking such as skid length. However the adjusted friction coefficient most certainly provides very accurate results taking into account the difference in test vehicle velocity to assessment vehicle velocity when considering entire braking distance.

When determining the velocity of a vehicle fitted with ABS during skidding, care should be taken to ensure the velocity at which test skids are conducted to determine the friction coefficient are less than the predicted velocity of the vehicle being analysed. Using the results from these tests,
the mean deceleration rate obtained in the vehicle with ABS to determine the velocity of the vehicle that was known to be travelling at 83.1 km/h, produced a range of over and underestimates when using the total braking distance to determine the vehicle velocity. The mean deceleration rate obtained at 30 km/h and 40 km/h both underestimated the actual velocity. The mean deceleration rate obtained at 50 km/h, 60 km/h and 80 km/h all produced overestimates. The overestimates were not more than 1.91 km/h above the actual velocity and only occurred based on the total braking distance. When using the skid distance only, to determine pre braking velocity, all calculations produced results that underestimated the true velocity.

4.6 VALIDATION

4.6.1 VALIDATION EXPERIMENTAL PROCEDURES

To validate the accuracy of the MEHEGAN prediction model to predict the likely friction coefficient of a road surface and various vehicle velocities I conducted a second series of tests (Table 4.3). The tests were performed in the same vehicle at a different location. The tests were conducted in
the driveway of Napier Park Nature Reserve, High Street, Road, Wheelers Hill, Victoria. The same procedure was followed as for series one with two tests being performed at 40 km/h, 50 km/h, 60 km/h, 70 km/h and 80 km/h with the ABS deactivated. No tests with ABS were performed.

4.6.2 PREDICTED RESULTS

FRICTION COEFFICIENT AT 41.1 KM/H WAS -0.840

Table 4.3 Predicted Friction Coefficient Using MEHEGAN Prediction Model and Modified MEHEGAN Prediction Model

<table>
<thead>
<tr>
<th>VEHICLE VELOCITY KM/H</th>
<th>PREDICTED RESULT USING MEHEGAN PREDICTION MODEL</th>
<th>PREDICTED RESULT USING MODIFIED MEHEGAN PREDICTION MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[ \mu_p = -0.982 \frac{n-m}{10} \times \mu^m ]</td>
<td>[ \mu_p = -0.982 \frac{n-m}{10} \times \mu^m \pm 0.95 ]</td>
</tr>
<tr>
<td>50.8</td>
<td>0.825</td>
<td>-0.786 – 0.866</td>
</tr>
<tr>
<td>60.6</td>
<td>0.810</td>
<td>-0.771 – 0.851</td>
</tr>
<tr>
<td>70.9</td>
<td>0.797</td>
<td>-0.758 – 0.835</td>
</tr>
<tr>
<td>80.4</td>
<td>-0.782</td>
<td>-0.743 – 0.821</td>
</tr>
</tbody>
</table>
4.6.3 VELOCITY RESULTS

4.6.3.1 VERIFICATION DECELERATION RATE TESTS

Table 4.4 Velocity calculations between 50 km/h and 80 km/h using friction coefficients obtained at 40 km/h

<table>
<thead>
<tr>
<th>VELOCITY KM/H</th>
<th>TEST RESULT</th>
<th>ERROR IF USING 0.840</th>
<th>CALCULATED VELOCITY USING -0.840 (km/h)</th>
<th>ERROR ON CALCULATED VELOCITY KM/H</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.8</td>
<td>-0.783</td>
<td>+0.057</td>
<td>52.45</td>
<td>+1.65</td>
</tr>
<tr>
<td>60.6</td>
<td>-0.786</td>
<td>+0.054</td>
<td>62.31</td>
<td>+1.71</td>
</tr>
<tr>
<td>70.9</td>
<td>-0.745</td>
<td>+0.095</td>
<td>70.04</td>
<td>-0.86</td>
</tr>
<tr>
<td>80.4</td>
<td>-0.732</td>
<td>+0.108</td>
<td>81.32</td>
<td>+0.92</td>
</tr>
</tbody>
</table>

Skid tests were performed at an average of 41.1 km/h, 50.8 km/h, 60.6 km/h, 70.9 km/h and 80.4 km/h to obtain the deceleration rate at each velocity. The distance of each braking section was also recorded, which allows the vehicle velocity at the commencement of braking to be calculated using the velocity from skid formula. Using the known braking distance, the velocity at commencement of braking was calculated using the deceleration rate obtained at 41.1 km/h. This was then used to determine the accuracy of this method when using a friction coefficient obtained at a lower test velocity compared to a subject vehicle velocity. At 51.8 km/h, 60.6 km/h and 80.4 km/h by using the friction obtained at 41.1
km/h the calculated velocity was higher than the vehicle velocity at commencement of braking. The over estimate ranged between 0.92 km/h and 1.71 km/h. At 70 km/h the velocity calculated was below the test vehicle velocity. It should be noted that the velocity from skid formula is based on using the length of a skid rather than braking distance. Braking distance is calculated using the Vericom brake test computer. Braking distance is longer than skid length. That is a vehicle driver will always have applied braking prior to the commencement of a skid mark becoming visible on a road. Using the known braking distance the velocity at commencement of braking the vehicle velocity was calculated using - 0.840g the friction coefficient obtained at 41.1 km/h
4.6.3.2 VERIFICATION DECELERATION RATE TESTS USING MEHEGAN PREDICTION MODEL

Table 4.5 Velocity calculations between 50 km/h and 80-km/h using friction coefficient obtained at 40 km/h

<table>
<thead>
<tr>
<th>VELOCITY KM/H</th>
<th>PREDICTED RESULT MEHEGAN PREDICTION (g)</th>
<th>CALCULATED VELOCITY USING MEHEGAN PREDICTION MODEL KM/H</th>
<th>ERROR ON CALCULATED VELOCITY KM/H</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.8</td>
<td>-0.825</td>
<td>51.99</td>
<td>+1.19</td>
</tr>
<tr>
<td>60.6</td>
<td>-0.810</td>
<td>61.18</td>
<td>+0.58</td>
</tr>
<tr>
<td>70.9</td>
<td>-0.797</td>
<td>68.23</td>
<td>-2.67</td>
</tr>
<tr>
<td>80.4</td>
<td>-0.782</td>
<td>78.59</td>
<td>-1.81</td>
</tr>
</tbody>
</table>

Using the MEHEGAN prediction model formula designed and the friction coefficient -0.840 g obtained at 41.1 km/h, the expected friction coefficient values were calculated as shown in Column 2 for values at 50.8 km/h, 60.6 km/h, 70.9 km/h and 80.4 km/h being the test velocities for which actual values were obtained. The purpose of using the MEHEGAN prediction model is to validate the formula for situations where a friction test cannot safely be conducted at the same velocity that a vehicle involved in a collision was travelling. For a collision reconstruction expert the ability to adjust friction coefficient values obtained at low velocities will
increase the accuracy of such work whilst allowing all testing to be safe. At 50 and 60 km/h these prediction friction coefficient values resulted in estimated velocity calculations that were higher than the actual velocity by up to 1.19 km/h. At 70 km/h and 80 km/h the estimated velocity calculations using the predicted friction coefficient values were lower than the actual velocity by up to 2.67 km/h. This margin of error is likely due to the nonlinear decrease in friction coefficient as vehicle velocity increases, preventing a ‘one size fits all’ approach as occurs when one formula is devised using a regression model.

### 4.6.3.3 VERIFICATION DECELERATION RATE TESTS USING MODIFIED MEHEGAN PREDICTION MODEL

Table 4.6 Velocity calculations between 50 km/h and 80-km/h using friction coefficient obtained at 40 km/h

<table>
<thead>
<tr>
<th>VELOCITY KM/H</th>
<th>PREDICTED RESULT USING MEHEGAN PREDICTION MODEL (g)</th>
<th>CALCULATED VELOCITY USING MEHEGAN PREDICTION MODEL KM/H</th>
<th>ERROR ON CALCULATED VELOCITY KM/H</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.8</td>
<td>-0.786 – 0.866</td>
<td>50.74 – 53.26</td>
<td>-0.06 - + 2.46</td>
</tr>
<tr>
<td>60.6</td>
<td>-0.771 – 0.851</td>
<td>59.69 – 62.34</td>
<td>-0.91 - +1.74</td>
</tr>
<tr>
<td>70.9</td>
<td>-0.758 – 0.835</td>
<td>66.54 – 69.84</td>
<td>-4.36 - -1.06</td>
</tr>
<tr>
<td>80.4</td>
<td>-0.743 – 0.821</td>
<td>76.48 – 80.39</td>
<td>-3.92 - -0.01</td>
</tr>
</tbody>
</table>
When using the devised MEHEGAN prediction model formula to predict the projected friction coefficient, the calculated velocities were still above the test velocity at 50.8 km/h and 60.6 km/h. Taking into account the nonlinear results and the difference between the results used to devise the equation and the results obtained in the validation testing, a margin of error of +/- 5% was considered. At 50.8 km/h and 60.6 km/h the actual test vehicle velocity fell within the calculated velocity +/- 5% modified model. At 70.9 km/h and 80.4 km/h the actual vehicle test velocity was higher than the entire range +/- 5% with the lower end of the range up to 4.36 km/h below the actual velocity. Whilst it is acceptable for a collision reconstructionist to under estimate the velocity an underestimate of 4.36 km/h is quite significant at 70.9 km/h is 6.14% under the actual velocity. As a result, the MEHEGAN prediction model was altered to include a margin of error of +/- 5% by multiplying the calculated predicted friction and multiplying it by 95%.

4.6.4 DISCUSSION

For a collision reconstruction expert, friction remains an elusive phenomenon that can be a critical factor to any collision reconstruction. If a friction coefficient value that is higher than that relative to the subject
vehicle is utilized in any calculation, then the end result will be a velocity that is higher than the actual velocity.

Preliminary testing identified that when a vehicle that is not fitted with ABS skids then the friction coefficient will decrease as vehicle velocity increases above 40 km/h. Often a vehicle involved in a collision is travelling at a velocity that is dangerous or too high for the environment. This prevents the collision reconstruction expert from conducting road friction analysis at the relevant velocity. For every km the test vehicle is below the subject vehicle the risk of over estimating velocity is increased.

Initial testing identified that the most significant decrease in friction coefficient occurred between 40 km/h and 70 km/h. At 40 km/h a friction coefficient obtained at -0.847 g would result in an over estimate of velocity by 3.4 km/h if then used on a vehicle travelling at 80 km/h. Using mathematical modeling the MEHEGAN prediction model formula was developed to allow predictions of friction coefficient at higher velocities based on results obtained at lower velocities. In the same series of testing the predicted friction at 80 km/h using the devised formula would be 0.788 g. By using the predicted friction coefficient the calculated velocity would be -0.13 km/h below the actual vehicle velocity.
A complete second series of testing was then conducted at a second location to verify the accuracy of the mathematical MEHEGAN prediction model to predict the projection of friction coefficient as velocity increases. Determining the friction coefficient projections for 50 km/h, 60 km/h, 70 km/h and 80 km/h were done using the mathematical model based on the friction coefficient recorded at 40 km/h. The projected results were then compared against actual results recorded to verify the accuracy and validity of the model. At 50 km/h and 60 km/h, the calculated velocity when using the friction coefficient predicted using the model was between 0.58 km/h and 1.19 km/h above the actual velocity. At 70 km/h and 80 km/h the calculated velocity was between 1.81 km/h and 2.67 km/h below the actual velocity, an error of +/- 3%.

Two different locations were used to verify the model and its validity. There was a difference of 2% between the friction coefficients obtained at 40 km/h at the two sites. Taking this into account the mathematical prediction model was varied to incorporate a margin of error of 5%, which should be sufficient to incorporate the variation at most sites. Using the modified prediction model and the result obtained from the verification testing the projection results all an underestimate of the actual friction coefficient for that location. For a collision reconstruction expert the use of a friction coefficient, which is lower than the actual friction coefficient, is acceptable,
as it will result in a velocity, which is lower than the actual velocity being analysed. Motor vehicle drivers who are involved in collisions while travelling at high velocity can be liable to both criminal and civil jurisdictions. For this reason it is not acceptable for a velocity to be calculated higher than the true velocity.

All velocity calculations in this research were based on the distance measured and recorded by the Vericom brake test computer. The distance is relative to the distance travelled by the vehicle from the initial application of braking. A collision reconstructionist is not provided with the total distance of braking but rather works with the tyre marks visible on the road way. Tyre marks are not left on the road immediately that braking is applied. The time from the brake application to the onset of visible skid marks on a road is defined as the transient period of the braking process (Neptune, 1995). According to Goudie (2000) the transient brake period is generally between 0.082 and 0.540 seconds with a vehicle velocity reduction of between 1 and 25 percent. This results in a velocity reduction of between 5% and 15%. Based on this, research using the friction coefficient obtained at 40 km/h can result in a velocity estimate, which is over by up to 4%. Therefore, if using visible tyre marks to determine the velocity of a vehicle, the velocity should be an underestimate even if using a friction coefficient, which is obtained at a velocity lower than the subject
vehicle. Using the mathematical projection model where velocity is being determined from tyre marks, would result in an underestimate of true vehicle velocity at the onset of braking at all velocities between 40 km/h and 80 km/h. The use of the modified projection model where the velocity is determined from tyre marks will result in an estimate that could likely be between 11% and 21%. Whilst underestimates are acceptable estimates up to 21% below are too low.

Where a velocity estimate is being performed using the friction coefficient values obtained from a test vehicle that is travelling considerably lower than the subject vehicle, then the projection model should be used in preference to the modified MEHEGAN prediction model.
4.7 FUTURE RESEARCH

The vehicle velocities that were tested in this research limit the validity of the MEHEGAN prediction model for use in all collision reconstructions. It appears that a plateau occurs around 70 km/h to 80 km/h for both vehicles with and without ABS. For conclusive validation of this model, testing would need to incorporate velocities up to 150 km/h. When using registered passenger vehicles and actual road surfaces safety becomes paramount for this testing. Safety is compromised as vehicle velocity increases.
CHAPTER 5

AMBIENT TEMPERATURE AND ITS EFFECT ON FRICTION

5.1 INTRODUCTION

The friction coefficient of a particular road surface and car tyre can be measured using a test vehicle and an accelerometer. However, the friction coefficient result can only be relevant to the conditions in which the testing occurred. This assumes that the friction coefficient of a road surface and paired car tyre is not affected by temperature or otherwise provides nothing more than a ‘good estimate’.

When a motor vehicle collision is being reconstructed, the road surface friction needs to be either measured or estimated. Where precision is necessary, then tests should be performed. It is not possible to perform tests in identical weather conditions to what was occurring at the time of the collision. There will always be a delay between the collision and the subsequent friction testing. The delay may be hours, days, weeks, months or even years. Despite the many other variables that may change between the collision and subsequent test due to time delay, consideration must be given to ambient temperature. A collision may occur at 2.00 am
when the ambient temperature is near to 0ºC (32ºF). Due to the necessary scene examination and evidence preservation, it is reasonable that the friction testing may not occur until 2.00 pm later that day. The temperature could reasonably increase by up to 25ºC (77ºF) in that time. If road surface/tyre friction is not affected by temperature then the temperature change will not be relevant, however, if it is relevant then it is critical to know what the affect is, to allow adjustment to friction test results to be made prior to reconstructing the collision and calculating vehicle velocity.

Early theories suggested that the coefficient of friction is independent of temperature (Wada 1993). Coulomb included the nondependent relationship between temperature and rubber in his laws first published in 1785. However, more recently when polymers such as rubber have developed and more research has been performed, researchers now believe that rubber friction is very sensitive to temperature. (Schallamach 1952, Takadoum 2007) The primary objective of this study is to experimentally determine the effects of ambient temperature on the friction coefficient of motor vehicle tyres and road surfaces.

Predominantly, the research looking at the effects of temperature, which has been conducted, specific to car tyres and road surfaces, has looked at
extremely cold temperatures more prevalent in the United States and the United Kingdom. Australia experiences temperate weather for most of the year. However, due to the size and its position over the Tropic of Capricorn, the climate can vary throughout the continent. Typically, the northern states have warm weather throughout the entire year with the southern states having cooler temperatures in Winter but still warm to hot in Summer. Australia is one of the driest continents on earth with an annual rainfall of less than 600 millimetres. Due to its position in the southern hemisphere, Australia’s seasons are opposite to the northern hemisphere where most research has been performed. December to February is Summer; March to May is autumn; June to August is Winter and September to November is Spring. The testing for this research was performed over all seasons.

All research was performed in the State of Victoria where the climate is marked by a range of different climate zones. The northwest of the state has dry regions while the northeast is covered in alpine snow regions. Victoria has a reputation forever changing weather but as a general rule the city has warm to hot summers, mild balmy spring and autumn and cool winters. Average temperatures are 25ºC in Summer and 14ºC in Winter. Rainfall is highest from May to October.
The objectives of this study are to identify how ambient temperature affects the tyre/road friction coefficient on dry bitumen road surface using modern passenger vehicles. The results of this study will increase the accuracy of motor vehicle collision reconstruction in a range of environmental conditions worldwide. Will friction coefficient of car tyres and road surfaces remain the same as ambient temperature increases? This research will provide collision investigators and reconstruction experts worldwide, a better understanding of the effects of vehicle velocity on the friction coefficient of the car tyres and road surfaces, specifically when ascertaining the road/tyre friction coefficient of a collision scene when testing is conducted after the collision is being analysed in substantially different ambient temperatures.

5.2 EXPERIMENTAL CONDITIONS

The experimental testing phase was performed randomly between July 2012 and January 2014. Tests were performed randomly in a range of temperatures between 3°C and 43°C. Time of day was not a factor and testing was based purely on ambient temperature with tests being performed both night and day. All tests were performed in dry conditions with no recent rainfall having been recorded in the preceding 12 hours. All
tests were performed with the ABS disabled as a result of fuse removal. ABS testing was not performed at the request of the vehicle owner due to the vehicle wear that would occur from such repetitive testing over a long period.

5.2.1 LOCATION

All tests were performed at Attwood Victoria Police Driver Training Facility, 505 Mickleham Road, Attwood, Victoria, Australia. (37.666ºS 144.887ºE) This is a private police facility, which is not open to the general public and primarily used to train members of Victoria Police in emergency driving techniques. The road is privately owned and has not been resurfaced since 2007. There were no resurfacing or significant repairs carried out on the road surface between July 2012 and January 2014. All tests were performed whilst driving the circuit in an anticlockwise direction. The dry tests were performed on the northern straight whilst travelling west. (See Fig. 5.1). The bitumen road surface is in excellent condition due to very low levels of vehicle traffic and the high level of maintenance, due to the high risk driving that occurs at the location. There were no noticeable condition changes during the period of testing. The area is well drained.
Fig. 5.1 Location of testing at Victoria Police Driver Training Facility, Attwood.

5.2.2 TEST VEHICLES

Tests were conducted in Australian built General Motors Holden (GMH) Commodore Omega four door sedans. There were two different vehicles used over the three years of testing. Both vehicles were of the same model having been built in 2010 and 2012 with no noted changes in production. The model, build and specifications of both vehicles were the same. The 3.0 litre V6, spark ignition direct injection vehicles were fitted with six velocity automatic transmissions. Ventilated disc brakes were fitted to both the front and rear. Rear wheel drive, the vehicle had antilock braking system (ABS) fitted as standard. The ABS was disengaged for all
tests. No performance modifications had been made to the vehicle with all braking, steering and suspension components fitted by the manufacturer as standard. The vehicle’s tested mass with two occupants, was 1762 kg. All vehicles had travelled less than 40,000 km at the time of tests. The vehicle type used in this study is depicted in Fig. 5.2

Fig 5.2 Holden Omega sedan used for all temperature testing
5.2.3 TYRES

At the time of testing, all vehicles were fitted with four Bridgestone Turanza ER3HZ tyres that were fitted to the vehicle at new. The 225/60 R16 tubeless steel belted radial tyres were considered to be a mid-range touring model by the manufacturer. The minimum tyre tread depth on any tyre was 4mm and all tyres were inflated to 34 PSI (2.3 x 10^5 Pa) prior to the commencement of testing. The tyres on all vehicles had been used for both country and city driving and no damage had been recorded or repairs carried out prior to the tests. Visual inspection showed no evidence of uneven wearing of the tyres. Tread pattern of Turanza ER3HZ tyre shown in Fig 5.3

Fig 5.3 Tread pattern of Bridgestone Turanza ER3HZ tyre
5.2.4 BRAKE TEST COMPUTER

The VC4000 Vericom brake test system was used on this primary research testing phase. The device has 3 major components: a crystal clock, an accelerometer and a microcontroller which measures the instantaneous G-force 100 times per second and can measure the difference between ABS and standard brakes. The VC4000 is activated at a 0.2 g threshold upon initiation of the brake pedal load cell. The device is attached to the windscreen of the test vehicle and is considered one of the most modern and reliable test devices to determine g-force. The g-force is measured within 0.001 g providing accuracy of 1%. Distance is recorded at an accuracy of 1% over 400 m and velocity is accurate within 1% up to 100 kmh. Therefore the g-force will not change unless the velocity changes. Vericom Brake Test Computer shown in Fig. 5.4
5.2.5 TEST VELOCITY

The series of skid tests were all performed at as close to 60km/h as possible. When the ABS fuse has been removed from the vehicle to disable the ABS the cruise control function does not work. Once the Vericom Brake Test Computer is activated, no application of braking can be made prior to the test braking application or the Vericom will activate early and provide a false result. It is necessary for the driver to accelerate while observing the speedometer and activate braking as near as possible to 60 km/h. Due to the process for human velocity estimation and braking,
no tests were conducted where braking was applied at 60.0 km/h precisely. The velocity ranges at which braking was activated was 47 km/h and 62 km/h.

5.3 METHODOLOGY

Tests were performed randomly over a 21 month period. A total of 111 tests were conducted with a minimum of three tests at each temperature with less than 10% variance between the three tests required before results were accepted. Each vehicle had a driver and observer/recorder. The author was the driver for most tests, although in one series of continuous 24 hour testing, the driver was changed every eight hours due to fatigue considerations. Testing was conducted on the north side of the lap circuit whilst travelling west. Once the vehicle test velocity was attained (60 km/h), the foot brake was activated with maximum pressure. Pressure remained 100% until the vehicle came to a complete stop and the results were displayed on the Vericom brake testing computer display screen. All tests were performed with the ABS off. Testing position on the roadway remained in the same general area but was gradually brought forward to prevent skids being consistently performed over the top of each other,
particularly in the hot weather conditions where considerable scuffing was occurring. Once ABS is disabled the speedometer in the vehicle does not always display, resulting in velocity estimation by the driver prior to braking application.

5.4 RESULTS

As ambient temperature increased from 3°C to 43°C the friction coefficient of car tyres on a paired road surface increased from -0.630g to -0.889g. The increase was essentially linear with an average increase of -0.06 g for each increase of 10°C. When observing the average of three results at each temperature, an inconsistent spike in results was observed at 26°C - 28°C. The increase in friction coefficient from 25°C to 26°C was -0.029 g compared to the expected linear increase of -0.006 g. Although the three results at 26°C were within 10% of each other, the initial test provided a friction coefficient of -0.801 g followed by the two more expected results of -0.771 g and -0.777 g. The results obtained at 26°C and 27°C are significantly above the line of best fit but still fell within the standard error. In thirty-three of the thirty seven series of tests for temperatures at which friction coefficient was tested, the friction coefficient observed in the third
test was lower than the first test (Table 5.1). The strength of the results is high providing clear evidence that for motor vehicle tyres and the paired road surface, as ambient temperature increases, the friction coefficient also increases. There were seven instances where a very small reduction in the deceleration rate over three tests was observed when the ambient temperature increased by 1°C. However, this reduction was always immediately followed by an increase in friction coefficient as the ambient temperature was again increased by 1°C. Where a decrease in friction coefficient was observed despite an increase in ambient temperature, the decrease was never less than the friction coefficient observed in the previous result.
Table 5.1 Deceleration rate of a Vehicle Sliding on Bitumen with ABS disabled at a range of temperatures between 3°C and 43°C

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Average friction coefficient (µ)</th>
<th>Mean friction coefficient (µ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>-0.630 -0.634 -0.641</td>
<td>-0.635</td>
</tr>
<tr>
<td>4</td>
<td>-0.665 -0.663 -0.660</td>
<td>-0.662</td>
</tr>
<tr>
<td>5</td>
<td>-0.669 -0.666 -0.660</td>
<td>-0.665</td>
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<tr>
<td>6</td>
<td>-0.672 -0.671 -0.664</td>
<td>-0.669</td>
</tr>
<tr>
<td>7</td>
<td>-0.680 -0.677 -0.671</td>
<td>-0.675</td>
</tr>
<tr>
<td>8</td>
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<td></td>
</tr>
<tr>
<td>9</td>
<td>-0.674 -0.674 -0.671</td>
<td>-0.672</td>
</tr>
<tr>
<td>10</td>
<td>-0.684 -0.681 -0.673</td>
<td>-0.680</td>
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<td>-0.682</td>
</tr>
<tr>
<td>12</td>
<td>-0.696 -0.687 -0.694</td>
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<tr>
<td>13</td>
<td>-0.696 -0.698 -0.694</td>
<td>-0.696</td>
</tr>
<tr>
<td>14</td>
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<td></td>
</tr>
<tr>
<td>15</td>
<td>-0.704 -0.701</td>
<td>-0.699</td>
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<td>-0.692</td>
<td>-0.707</td>
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<tr>
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</tr>
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</tr>
<tr>
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<td>36</td>
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<td>37</td>
<td></td>
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</tr>
<tr>
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<td>-0.829</td>
</tr>
<tr>
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<td>-0.833</td>
<td>-0.840</td>
</tr>
<tr>
<td>40</td>
<td>-0.834</td>
<td>-0.835</td>
</tr>
<tr>
<td>41</td>
<td>-0.847</td>
<td>-0.846</td>
</tr>
<tr>
<td>42</td>
<td></td>
<td>Not Tested</td>
</tr>
<tr>
<td>43</td>
<td>-0.889</td>
<td>-0.860</td>
</tr>
</tbody>
</table>
Fig 5.5  deceleration rate of a Vehicle Sliding on Bitumen with ABS disabled between 3°C and 43°C
5.5 DISCUSSION

The friction coefficient of motor vehicle tyres and paired road surfaces will increase as the ambient temperature increases. There is a strong positive linear relationship between the two quantitative variables, temperature and friction coefficient, with minimal random variation. The correlation coefficient \( r = 0.983 \) supports a high degree of correlation between the two variables with 1.0 the highest degree of relationship possible. The coefficient of determination \( r^2 = 0.968 \) suggests that 96.8% of the friction coefficient is directly accounted for by ambient temperature. There is a direct relationship between the independent (ambient temperature) and dependent (friction coefficient) variables.

The tests were all performed randomly over a twenty-one month period. At each temperature, the complete series of three tests were conducted in the same session. There was an unexpected escalation in friction coefficient results observed at 26°C and 27°C. Both these series of tests were conducted on the same day using the same vehicle and same driver. The author was not the driver for these tests. These tests were not performed on the same day as the tests conducted at 25°C or 28°C. Whilst the results are not statistically inconsistent they are certainly
unexpectedly high. It is likely that these results were high due to a variable other than temperature.

In thirty three of thirty seven tests series, the friction coefficient decreased from the first test to the third test despite that fact that the friction coefficient of the car tyres and paired road surface increased as temperature increased. Friction always causes heat. The greater the friction that is required to stop a vehicle, the greater the amount of heat that is generated during braking. Therefore, the temperature of the brake components rises as the brakes are applied. Research has shown that one emergency stop at 96 km/h can raise brake lining temperatures by more than 70°C (Friction Brake Theory). Repeated heavy stops such as that necessary to cause a vehicle to skid, can continue to raise the temperature by equal amounts. The results are clear and provide strong evidence that the friction coefficient of car tyres and road surfaces will increase as ambient temperatures increase. It is likely that the small decreases observed in most three test series are due to the increased heating of the braking components not any affects of ambient temperature. Heat dissipation is the heat removed from brake friction surfaces by direct transfer to the surrounding air. Modern brake systems are designed to provide the best possible heat dissipation aimed to maintain the highest braking efficiency possible. Despite the design, friction always causes
heat. Three heavy brake tests in fast succession will have an effect of the
heat generated within the brakes and subsequently may be the cause for
the reduction in friction coefficient of the car tyres and road surfaces
observed in sequential tests, therefore explaining the decrease in results.

With the results providing evidence of such a strong positive linear
relationship between temperature and friction coefficient, the author
believes that friction predictions for a range of ambient temperatures is
possible using the carefully developed HARTMAN prediction model.

Based on a total braking distance of 30.0 metres, it is possible to
determine the effect of using a friction coefficient obtained at 3°C
compared to 43°C by establishing the velocity of a vehicle at the
commencement of braking.

Equation 1:

\[ V_i = \sqrt{V_e^2 - 2ad} \]

Where:

\( V_i \) = Initial Velocity (m/s^2)

\( V_e \) = End Velocity (m/s^2)

\( a \) = acceleration (average g x 9.81)

\( d \) = distance (m)
1) **Velocity of vehicle established using friction coefficient obtained at 3°C based on 30 metres braking**

\[
V_i = \sqrt{0^2 - (2 \times 9.81 \times -0.635 \times 30.0)}
\]

\[V_i = 19.33 \text{ m/s}^2, 69.58 \text{ km/h}\]

2) **Velocity of vehicle established using friction coefficient obtained at 13°C based on 30 metres braking**

\[
V_i = \sqrt{0^2 - (2 \times 9.81 \times -0.696 \times 30.0)}
\]

\[V_i = 20.24 \text{ m/s}^2, 72.86 \text{ km/h}\]
3) Velocity of vehicle established using friction coefficient obtained at 23°C based on 30 metres braking

\[ V_i = \sqrt{0^2 - (2 \times 9.81 \times -0.740 \times 30.0)} \]

\[ V_i = 20.87 \text{ m/s}^2, 75.13 \text{ km/h} \]

4) Velocity of vehicle established using friction coefficient obtained at 33°C based on 30 metres braking

\[ V_i = \sqrt{0^2 - (2 \times 9.81 \times -0.797 \times 30.0)} \]

\[ V_i = 21.65 \text{ m/s}^2, 77.97 \text{ km/h} \]
5) **Velocity of vehicle established using friction coefficient**

obtained at \(43^\circ\text{C}\) based on 30 metres braking

\[
V_i = \sqrt{0^2 - (2 \times 9.81 \times -0.862 \times 30.0)}
\]

\[
V_i = 22.52 \text{ m/s}^2, 81.07 \text{ km/h}
\]

When a collision reconstructionist is performing a collision analysis and velocity reconstruction, it is generally for a collision which has already occurred. Any type of test being used to determine the friction coefficient of the motor vehicle tyres and paired road surface relative to the collision can not be performed in identical conditions to what occurred at the time of the collision. If there is a substantial difference in the temperature at the time of the collision compared to the time of testing the temperature then the difference must be considered and necessary adjustments made to the friction coefficient being used for speed determination. As ambient temperature increases, the relative friction coefficient increases.
A difference in ambient temperature between the time of a collision and the time of friction coefficient analysis of 10°C will result in a velocity analysis, which is up 3 km/h out. If it is warmer at the time of testing compared to the time of the collision then the analysis will give a velocity estimation which is higher than the true velocity. If it is cooler at the time of testing compared to the time of the collision then the velocity analysis will be too low. This is based on a vehicle analysis at around 70 km/h. As the velocity being analysed increases then the margin of error will also increase. A temperature difference of 20°C will result in a margin of error of around 5 km/h for a 70 km/h collision and a 40°C temperature difference from the time of the collision to the time of testing will result in a velocity analysis, which is up to 10 km/h incorrect. A collision analysis for a vehicle travelling around 120 km/h would be up to 17 km/h out if there was a temperature difference of up to 40°C between the collision and subsequent testing.

In many instances collision reconstruction is being performed to provide critical evidence of the velocity of a vehicle prior to a collision. This evidence may be crucial for successful prosecution against drivers who are guilty of criminal offences, which have resulted in the death or serious injury of other road users. It is not acceptable for a collision reconstructionist to determine a vehicle travelling velocity which is either
higher than the true velocity or lower. If friction tests are performed in significantly different temperatures from the temperature when the collision occurred, it is possible that the velocity determination could be out by more than 10 km/h. If it was cooler at the time of the collision compared to the tests, then the velocity analysis will be too high. If it was warmer at the time of the collision compared to the test time then the velocity analysis will be too low. It is not possible to perform the tests in the same conditions as the collision conditions. It is however possible to determine the temperature at the time of the collision using recorded weather data. If ambient temperature at the time of the collision can be determined then the HARTMAN prediction model can be used to determine the friction coefficient of the road surface and car tyres relevant to the collision, using a friction coefficient result obtained at another time.
Equation 3. HARTMAN prediction model:

\[ \mu_p = \mu_t \Delta T (0.0071 \mu_t \Delta T) \]

Where:

- \( \mu_p \) = Predicted Friction Coefficient
- \( \mu_t \) = Measured Friction Coefficient
- 0.0071 = Constant based on regression
- \( \Delta T \) = Difference in ambient temperature between the collision under analysis and the friction coefficient test

Friction Coefficient can be predicted for a range of temperatures used the HARTMAN prediction model.

6) Determining the friction coefficient at 3°C using a friction coefficient value obtained at 43°C:

\[ \mu_p = \mu_t - (0.0071 \mu_t \Delta T) \]

\[ \mu_p = -0.862 - [0.0071 \times -0.862 \times (43 - 3)] \]

\[ \mu_p = -0.618 \text{ g} \]
7) **Vehicle velocity at 3ºC determined using the adjusted friction coefficient based on braking distance of 30.0 metres:**

\[ Vi = \sqrt{0^2 - (2 \times 9.81 \times -0.618 \times 30.0)} \]

Velocity = 19.07 m/s\(^2\), 68.66kph (underestimate by 0.93 km/h)

8) **Vehicle velocity at 3ºC determined using the friction coefficient obtained at 3ºC based on braking distance of 30.0 metres:**

\[ Vi = \sqrt{0^2 - (2 \times 9.81 \times -0.635 \times 30.0)} \]

Velocity = 19.33 m/s\(^2\), 69.59 km/h

9) **Vehicle velocity at 3ºC determined using the friction coefficient obtained at 43ºC based on braking distance of 30.0 metres:**

\[ Vi = \sqrt{0^2 - (2 \times 9.81 \times -0.862 \times 30.0)} \]

Velocity = 22.52 m/s\(^2\), 81.07kph (overestimate by 11.48 km/h)
Using the friction coefficient obtained at 3ºC, the velocity of a vehicle which leaves 30.0 metres of skids when the ambient temperature is 3ºC can be determined to be about 69.59 km/h at the commencement of skidding. If the same skids marks of 30.0 metres, which were left in ambient temperature of 3ºC, were being assessed to determine velocity at the commencement of skid marks and the friction coefficient was determined using tests at 43ºC, then the velocity of the vehicle at the commencement of the marks would be calculated at 81.07kph. That is more than 10 km/h higher than the velocity of the vehicle really would be.

Using the prediction model to determine the likely friction coefficient at 3ºC based on tests conducted at 43ºC then the velocity at the commencement of skidding would be determined to be about 68.66 km/h. This is less than 1 km/h less that the true velocity of the vehicle.

For a collision reconstructionist, when determining vehicle velocity which is intended to prove or disprove the commission of a criminal offence. it is critical that the calculated velocity is not greater than the true velocity. Using the prediction model to determine the ambient temperature effect of friction coefficient will assist in ensuring that incorrectly high velocity determinations are not made.
5.6 VALIDATION

Table 5.2 Measured deceleration rate and Predicted Friction Coefficient Using the HARTMAN Prediction Model at a Range of Ambient Temperatures Between 3°C and 43°C

<table>
<thead>
<tr>
<th>AMBIENT TEMPERATURE (°C)</th>
<th>FRICTION COEFFICIENT TEST RESULT (µ)</th>
<th>PREDICTED FRICTION COEFFICIENT USING HARTMAN PREDICTION MODEL</th>
<th>CALCULATED ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>µ_p = µ_t ±(0.0071 µ_t ΔT)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-0.635</td>
<td>-0.618</td>
<td>-0.017</td>
</tr>
<tr>
<td>4</td>
<td>-0.662</td>
<td>-0.624</td>
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<td>+0.013</td>
</tr>
<tr>
<td>22</td>
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<td>-0.734</td>
<td>+0.003</td>
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<tr>
<td>23</td>
<td>-0.740</td>
<td>-0.740</td>
<td>0.000</td>
</tr>
<tr>
<td>24</td>
<td>-0.731</td>
<td>-0.746</td>
<td>+0.015</td>
</tr>
<tr>
<td>25</td>
<td>-0.754</td>
<td>-0.752</td>
<td>-0.002</td>
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<tr>
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<td>-0.783</td>
<td>-0.758</td>
<td>-0.025</td>
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<td>-0.764</td>
<td>-0.020</td>
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<td>-0.777</td>
<td>-0.771</td>
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<td>-0.783</td>
<td>0.000</td>
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<td>+0.004</td>
</tr>
<tr>
<td>34</td>
<td>-0.813</td>
<td>-0.807</td>
<td>-0.006</td>
</tr>
<tr>
<td>35</td>
<td>-0.814</td>
<td>-0.813</td>
<td>-0.001</td>
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<td>+0.001</td>
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<tr>
<td>39</td>
<td>-0.832</td>
<td>-0.838</td>
<td>+0.006</td>
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</tbody>
</table>
The HARTMAN prediction model was used to determine the expected friction coefficient for a range of ambient temperatures. The greatest error was observed where there was a temperature difference of 37°C when the observed error was -0.056 g. This margin of error falls well within acceptable levels of difference across a range of friction coefficient values for one variable. That is, if three results were recorded at one temperature, those three results would generally be considered accurate and reliable if they fell within a range of -0.06 g. This is an accepted difference between three tests where identical results are unlikely and not expected. When using the friction coefficient values to determine vehicle velocity, a difference of 0.056 g would effect the calculated velocity by less than 1 km/h. However, this difference was an underestimate and therefore the calculated velocity would be less that the true velocity by less than 1km/h. For six of the thirty temperatures analysed, the predicted friction coefficient was identical to the measured friction coefficient, there was no margin of error. For 13 out of 37 tests, the prediction friction coefficient was higher than the measurement friction coefficient. The most significant difference was observed at 31°C where the prediction friction coefficient was -0.862 and the measured coefficient was -0.850.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Predicted Friction Coefficient</th>
<th>Measured Friction Coefficient</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>-0.831</td>
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<tr>
<td>41</td>
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<td>-0.850</td>
<td>+0.009</td>
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<tr>
<td>43</td>
<td>-0.862</td>
<td>-0.862</td>
<td>0.000</td>
</tr>
</tbody>
</table>
coefficient was 0.013 higher than the actual measured friction coefficient. This difference is well within an expected range. A difference of 0.013 could over estimate the velocity by 0.6 km/h. Since it is best practice for collision reconstruction experts to round all calculations down, it is unlikely that this would have any effect on the overall result and subsequent collision analysis. Without the prediction formula, the calculation could be overestimated by more than 10 km/h if the ambient temperature is not taken into account when measuring the friction coefficient.
The prediction model provides an ability to predict road/tyre friction coefficient efficiently and reliably. The comparison graph highlights the strength of the formula and its application. The measured friction coefficient for any specific location and circumstance will vary slightly with identical results repeated rarely and almost never. The difference seen
between the measured friction and predicted friction is within acceptable
difference for two measured tests at all temperatures. That is, the
difference between the measured and predicted friction coefficient is never
more than 10%, which is the accepted difference. In this model the
greatest difference between the measured friction and the predicted
friction is less than 5% highlighting the strength of the reliability of this
model and its application to friction coefficient prediction.
Vehicle velocity can be determined when a visible braking tyre skid is evident. This is very common in motor vehicle collisions both pre impact and post impact. Whilst the method is regularly used to determine the pre impact velocity of a vehicle the travelling velocity of the vehicle will actually be higher due to the percentage of slowing which occurs between the initial application of braking and the subsequent onset of skidding once the wheels become locked. What is really being calculated is the velocity of the vehicle at the commencement of skidding. For a collision reconstructionist, the calculated velocity will be less than the travelling velocity and therefore it is a reliable method to be used to determine vehicle velocity even in criminal prosecution.

Vehicle speed can be determined using the Velocity from Skid formula:

**Equation 3.**

\[
\text{Speed} = \sqrt{254 \times d \times f}
\]

Where:

254 is constant

d = length of the visible skid in metres

f = friction coefficient
Figure 5.7 depicts the vehicle speed which can be determined for a 30.0 metre skid using the measured friction coefficient at each temperature range, the predicted friction coefficient using the HARTMAN prediction model for temperatures between 3°C and 43°C and the single friction coefficient measured at 43°C. The effect of using the single measured friction coefficient, irrespective of the difference between the temperature at the time the skid was left and the time the subsequent test was performed, will vary depending on the difference between the two temperatures. The greater the difference between temperatures, the greater the inaccuracy in the velocity that is calculated. Figure 5.7 shows the effect of using a single measured friction coefficient for temperature differences up to 40°C. If the temperature difference between the test and the analysed collision/skid is 40°C then the calculated velocity could be incorrect by over 11.4 km/h. If the test to determine the friction coefficient is performed in conditions, which are cooler than they were when the skid was left, then the calculated velocity will be an underestimate by up to 11.4 km/h. If the friction coefficient test is conducted in conditions which are warmer than they were when the skids were left then the calculated velocity will be an over estimate by 11.4 km/h.
When using the HARTMAN prediction model to predict the friction coefficient at the time of a collision using a friction coefficient that was obtained at another time, the use of the velocity from skid formula to determine vehicle velocity is enhanced significantly. When using the prediction model to determine the likely friction, the calculated vehicle velocity was within 2 km/h at all temperatures.

Using the prediction model, the prediction friction coefficient was identical to the measured friction coefficient on six of thirty seven tests. The prediction model overestimated the friction coefficient in thirteen of the thirty seven samples. Where the friction coefficient was overestimated the subsequent vehicle velocity calculation was also overestimated. However, the overestimation was never more than 0.66 km/h. Where the friction coefficient was underestimated the result was an underestimate of velocity by up to 2 km/h. When compared to the use of a single measured friction coefficient for all temperature conditions the prediction model provides an accurate and very reliable method to determine the friction coefficient of the road surface and the car tyres relevant to ambient temperature.

The use of the prediction model to determine friction coefficient is critical where the difference between the ambient temperatures at the time of testing is significantly different from the time, which is being analysed.
Where the difference in ambient temperature is within 5°C the difference in velocity calculation would be less than 2 km/h. If the ambient temperature at the time of testing is less that it was at the time of the collision/skidding then the calculated velocity will be below the actual velocity and therefore, the use of the prediction model is not so important. Where the ambient temperature is higher at the time of testing then the prediction model should be used to ensure that any subsequent velocity calculation is not higher than the actual velocity. If the ambient temperature is different by more than 10°C whether higher or lower, then the HARTMAN prediction model should be used to provide a more accurate and reliable friction coefficient and subsequent velocity determination.

5.7 FUTURE RESEARCH

The research performed aspired to provide an analysis of the effect of ambient temperature on the friction coefficient of motor vehicle tyres and paired road surfaces for an extensive range of temperatures prevalent in Australia and relevant to Australian conditions.

Based on the determination that the friction coefficient of car tyres and road surfaces is effected by ambient temperature, the effects at below 0°C
temperatures would be relevant. Friction Coefficient research relevant to car tyres and road surfaces have predominantly been conducted in the United States of America and parts of Europe. Both regions are able to provide ideal conditions to perform such testing which most certainly would be relevant.

Further analysis could also be considered in relation to the observation of the decreasing friction coefficient observed between each series of tests. Based on this research we know that as ambient temperature increases the friction coefficient increases. However, in thirty of the thirty seven series of tests the friction coefficient decreased from test one to test three. Ideally analysis could be performed to determine whether the reduction in friction coefficient is due to the heating of the rubber between tests or alternatively heating of braking components of the vehicle.
CHAPTER 6

RAINFALL AND ITS EFFECT ON FRICTION

6.1 INTRODUCTION

Simplistic understanding of the friction phenomenon suggests that lubricants including water will lower the friction and reduce the wear between two sliding solid bodies. When considering roads, there is an expectation that most surfaces will be covered with a layer of oil deposited by both moving and stationary vehicles. The oil will act as a lubricant and lower the friction coefficient of car tyres and road surfaces in both wet and dry conditions. But when combined with water in rainfall type situations the expectation is that the friction coefficient will be reduced significantly.

It is believed that the single most important factor effecting road-tyre friction is the presence of water in various forms. Previous research suggests that it is the depth of the water that is crucial in determining the extent of the effect that the water has on the friction coefficient between car tyres and road surfaces. There is clear distinction between the effects of thin water layers in comparison to thick water layers. During rainfall the
depth of water rarely exceeds 2mm and is typically 1mm or less. Dissipation of the water is facilitated by both the road and tyre design.

Until recent years, there has been an accepted belief that water as a lubricant reduces the friction coefficient of car tyres and road surfaces. In 2001, Claeys identified that specific to road-tyre friction, the depth of the water layer is critical. Thin water layers most certainly reduce the friction coefficient by causing a complete loss in contact between the two surfaces. However, as the layer of water becomes thick, extra force is generated forward of the tyre due to an accumulation of water. This increases the forces acting against the tyre and subsequently increases the friction coefficient. This will occur until either the vehicle slows enough that the rate of dissipation increases or hydroplaning occurs. If hydroplaning does not occur then the friction coefficient will increase as water depth increases.

It has been an expectation and a practice for a collision reconstructionist to reduce the measured friction coefficient obtained in dry conditions by -0.1 to -0.2 g if the collision being assessed had occurred in wet or raining conditions. The heavier the rain was reported to be, the greater the reduction in friction coefficient when adjusting dry result values.
In 2013, since this research was conducted, a paper was published in SAE International. The paper titled *Friction, Tread Depth and Water: Laboratory Investigations of Passenger Car Tire Cornering Performance under Minimally – Wet Conditions* (Blythe, Seguin) considered the effects of water depth on the friction coefficient of car tyres and road surfaces. The research was performed in laboratory conditions using three dimensional dynamic vehicle simulations. The work concentrated on tread depth primarily but in addition did consider water depth. The work reported that at 64 km/h, with water depths greater than 1.27 mm, the friction coefficient of the car tyre on the road surface was similar to dry friction results.

This research supports the work of Blythe and Seguin and relates the laboratory tyre test results to real world highway conditions as recommended in their paper published in 2013. The paper does suggest that as vehicle velocity increases, the friction coefficient will decrease even in deep water conditions. The effects of velocity in rainfall testing were not covered in this work.

The objectives of this study were to identify how rainfall affects the friction coefficient of motor vehicle tyres and paired road surfaces without ABS. Simplistic approaches suggest that water, as a lubricant will result in a
reduction in friction coefficient. However, to the surprise of many, more recent and specific work suggests that in heavy rainfall, when water depths are greater than 1mm above the level asperities of the road surface, the friction coefficient may increase. The results of this study will increase the accuracy of vehicle velocity estimates in collision reconstruction for vehicles in raining and wet conditions. Will friction coefficient increase, decrease or remain the same in heavy rainfall conditions? This research will provide collision investigators and reconstruction experts worldwide a better understanding of the effects of rainfall and water on the friction coefficient of car tyres and road surfaces specifically when a collision occurred in a period of heavy rainfall or post rainfall.

6.2 EXPERIMENTAL CONDITIONS

The experimental testing phase was performed on 12 August 2012. The entire test phase involved three series of tests with each series comprising a total of twenty tests. The three series of tests included pre rainfall (dry), rainfall (rain) and post rainfall (wet) tests. The ambient temperature was 13°C with diminutive variation only. The entire testing phase was
complete within three hours between 9:40 am and 12:40 pm. The dry phase was completed first and was performed in an area with no rainfall recorded in the preceding three days. The rain phase was completed next using artificial rainfall. The wet phase was completed last on the area previously used for dry and rain testing. There was no notable wind recorded and conditions were essentially mild to cool. Spatial cloud cover was evident.

6.2.1 LOCATION

The test phase was performed at the Country Fire Authority (CFA) Training College, 4549 Geelong-Ballan Road, Fiskville, Victoria, Australia (37.683812°S 144.218707°E). This is a private training college for members of the CFA. The CFA is predominantly a volunteer fire and emergency service that has legislative responsibility for fire and emergencies in regional Victoria. The CFA, Fiskville is used for general training including driver training. The road is privately owned and has not been resurfaced since 2001. The bitumen aggregate is in good condition with no obvious faults or defects. The area of testing is utilized as a thoroughfare with low volume, low speed traffic. The road runs in a
general north south direction with all tests performed whilst travelling in a northerly direction (Fig 6.1).

![Fig. 6.1 CFA Training College, Fiskville](image)

**6.2.2 TEST VEHICLE**

Tests were conducted in an Australian built General Motors Holden (GMH) Commodore Omega four-door sedan. One vehicle was used for the three series of tests. The vehicle was built in 2010 and first registered in 2011. The 3.0 litre V6, spark ignition direct injection vehicle was fitted with six
speed automatic transmission. Ventilated disc brakes were fitted to both the front and rear. Rear wheel drive, the vehicle had antilock braking system (ABS) fitted as standard. The ABS was disengaged for all tests. No performance modifications had been made to the vehicle with all braking, steering and suspension components fitted by the manufacturer as standard. The vehicle’s tested mass with two occupants, was 1762 kg. The vehicle had travelled 12755 kilometres at the time of tests. The vehicle type used in this study is depicted in Fig. 6.2.
6.2.3 TYRES

At the time of testing, the vehicle was fitted with four Bridgestone Turanza ER3HZ tyres, which were fitted to the vehicle at new. The 225/60 R16 tubeless steel belted radial tyres were considered to be a mid-range touring model by the manufacturer. The minimum tyre tread depth on any tyre was 6mm and all tyres were inflated to 34 PSI (2.3 x 10^5 Pa) prior to the commencement of testing. The tyres had been used for both country and city driving and no damage had been recorded or repairs carried out on any tyre prior to the tests. Visual inspection showed no evidence of uneven wearing of the tyres. The tyres were all aged equally. The tyres had travelled 12,755 kilometres from new at the time of testing.

6.2.4 BRAKE TEST COMPUTER

All tests within this primary research testing phase were performed using a VC4000 Vericom brake test system. The device has 3 major components: a crystal clock, an accelerometer and a microcontroller which measures the instantaneous G-force 100 times per second and can measure the difference between ABS and standard brakes. The VC4000 is activated at a 0.2 g threshold upon initiation of the brake pedal load cell. The device is
attached to the windscreen of the test vehicle and is considered one of the most modern and reliable test devices to determine g-force. The g-force is measured within 0.001 g providing accuracy of 1%. Distance is recorded at an accuracy of 1% over 400 m and velocity is accurate within 1% up to 100 kmh. Therefore the g-force will not change unless the velocity changes. The brake test computer was calibrated prior to each series of tests.

6.2.5 TEST VELOCITY

The series of skid tests were all performed at as close to 60km/h as possible. When the ABS fuse has been removed from the vehicle to disable the ABS, the cruise control function and speedometer display does not work. Once the Vericom brake test computer is activated, no application of braking can be made prior to the test braking application or the Vericom will activate early and provide a false result. It is necessary for the driver to accelerate while estimating the vehicle speed and then activate braking as near as possible to 60 km/h. Due to the process for human velocity estimation and brake application timing, no tests were
conducted where braking was applied at 60.0 km/h precisely. The velocity ranges at which braking was activated was 54 km/h and 64 km/h.

6.3 METHODOLOGY

The testing phase to examine the effect of rainfall and wet roads on the friction coefficient of car tyres and road surfaces was performed in one single session. All tests were performed at the same location in essentially the same conditions over a three hour period. The first series of tests were performed on a dry road. Twenty tests were performed over a one hour period with approximately three minutes between tests to allow cooling of the vehicle braking system. All tests were performed whilst travelling north. The ABS was disabled.
The rainfall testing series was performed following the dry testing. Twenty tests were performed whilst travelling north in the same location as the dry testing. Rainfall was artificially replicated using the high pressure hoses and recycled water from two fire fighting Scania pumpers from either side of the roadway. Each pumper was capable of pumping 4000 litres of water per minute. The hoses pumped water continuously for the entire testing period. The testing period was performed over a one hour period with approximately one test every three minutes providing a stationary
period of at least two minutes to facilitate cooling of the braking system. The pumping of water replicated periods of very heavy rainfall. A thick layer of water was evident on the travelling path of the vehicle and in the braking location (Fig 6.4 – 6.7).

Fig 6.4 Fire hose pumping water to simulate heavy rainfall conditions.
Fig 6.5 Simulated rainfall direction and vehicle during braking
Fig 6.6 Vehicle during braking throughout simulated rainfall testing
The third and final series of tests were performed in the same location following straight after the simulated rainfall testing. The hoses were turned off and twenty consecutive tests were performed in the same location as the dry and rainfall testing. The series of twenty tests were performed over one hour with the surface being lightly sprayed at twenty and forty minutes to maintain a wet surface similar to what would be expected immediately following rainfall. There was a rest period of up to three minutes after each test to allow cooling of the braking components.
Fig 6.8 Vehicle during skid resistance test on wet surface
### 6.4 RESULT

Table 6.1 Deceleration rate Before, During and After Simulated Rainfall

<table>
<thead>
<tr>
<th>Test No.</th>
<th>deceleration rate RAINFALL (g)</th>
<th>deceleration rate DRY (g)</th>
<th>deceleration rate WET (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.824</td>
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<td>-0.659</td>
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<tr>
<td>2</td>
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<td>-0.784</td>
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<tr>
<td>5</td>
<td>-0.778</td>
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<tr>
<td>6</td>
<td>-0.835</td>
<td>-0.823</td>
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<td>20</td>
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</table>
Fig 6.9 Friction Coefficient before, during and after simulated rainfall
Fig 6.10  Average of friction coefficient results before, during and after simulated rainfall

Average Friction Coefficient Before, During and After Rainfall

- Average Friction Coefficient, Rainfall, $-0.816$
- Average Friction Coefficient, Dry, $-0.791$
- Average Friction Coefficient, Wet, $-0.709$
Fig 6.11  Average of friction coefficient results before, during and after simulated rainfall in Ascending Order
The deceleration rate was calculated for twenty tests before, during and after rainfall. All tests were conducted consecutively for each series in the order of before (dry), during (rainfall) and after (wet) simulated rainfall. The deceleration rate during rainfall over twenty tests was -0.816 g compared to -0.791 g in dry conditions and -0.709 g on the wet surface after rain. There were no results on the wet road, which had a higher friction coefficient to any result that was obtained during the simulated rainfall. That is, the highest friction coefficient recorded on the wet road was lower than the lowest friction coefficient recorded during rainfall. In three of the tests conducted in the wet, the results were higher than the three lowest results obtained in the dry. Eight of the results obtained in the simulated rain conditions were higher than the highest results obtained in the dry conditions. There were five results, which occurred, in the dry conditions, which were lower than the lowest result obtained in the raining conditions. When comparing the average of the full twenty results, the deceleration rate measured in the raining conditions was 3.1% higher in the raining conditions compared to the dry conditions and 13.2% higher in the raining conditions compared to the wet conditions. The deceleration rate in the dry conditions was 10.4% higher than the wet conditions. In the raining conditions the average g was more than -0.1g higher compared to the wet conditions. The average g was -0.025g more in the raining conditions compared to the dry.
6.5 DISCUSSION

Contrary to significant volumes of research, the friction coefficient of a skidding vehicle tyre on a road surface is not reduced during periods of high rainfall. Compared to a dry road, the friction coefficient is likely to be around 3% higher in heavy rain in a vehicle travelling at around 60kph.

Consistent with previous research, the friction coefficient decreases significantly when the road is simply wet and there is no depth to the layer of water on the road. If the layer of water is below the level of asperity then the road is regarded as wet.

The author believes the depth of the water is the critical factor in determining the effect of rainfall on the friction coefficient of car tyres and road surfaces. Once the water in front of the sliding tyre becomes so deep that dissipation does not occur at a rate fast enough to remove a build up of water in the path ahead of the tyre, a wedge occurs which increases the resistance against the tyre as it slides. See Fig. 6.12. At very low water depths, the water between the tyre and the road surface reduces the friction coefficient between the two solid surfaces by acting as a lubricant. Once the layer becomes too deep to dissipate the wedge will occur. Theoretically, if the friction coefficient is increased due to a wedge forming ahead of the tyre as a result of an inability for the water to dissipate, then
road design and tyre tread also play key roles in determining whether the friction coefficient will increase or decrease in periods of rainfall. The water depth at which the friction coefficient increases is likely to be affected by these factors. Therefore, it is unlikely that simply determining a depth at which the friction coefficient will begin to increase would be possible. That is, a quality tyre with good tread depth and good dissipation properties is likely to be more efficient in keeping the path ahead clear of water, and without the formation of the wedge the friction coefficient will decrease in the same rainfall that another tyre may fail to dissipate. As opposed to temperature where the temperature at the time of a collision can reasonably be estimated, it is not possible to estimate water depth. Apart from knowing the rate of rainfall, each road and each tyre may vary the effect of the water build up to some degree. The macro and micro textures of the road in addition to cross fall and gradient will further affect this. Prediction of friction coefficient of car tyres and road surfaces based on the depth of water simply cannot possibly to be used in collision reconstruction.
If analysing a collision, which has already occurred, quantifying the rainfall at the time of the collision in the exact location and the exact time is virtually impossible. Even if the quantity of rain could be determined then it is basically impossible to determine what the dissipation properties of the tyre and the road surface were and therefore it is very difficult to determining whether the wedge of water formed forward of the tyre and if so what effect that wedge had.
It should be possible in controlled laboratory testing, to determine the effect of a water wedge and a range of depths for a range of tyres and aggregate types and known velocities. It is unlikely that the findings could ever be used to validate friction coefficient prediction formulas for use in collision reconstruction based on the influence of rainfall on a skidding vehicle.
Based on the results of this research, the effect of using the friction coefficient obtained on a wet surface, for a tyre that was locked and sliding on a road surface in heavy rainfall conditions, it is likely that a collision reconstructionist will underestimate the true speed of the vehicle by applying the friction coefficient obtained during testing on a wet surface. Without knowing whether a wedge of water formed forward of the tyre it is not possible to know whether the friction coefficient will be affected by the rainfall and therefore the wet friction must be used. Based on a sliding distance of 30.0 metres, the effect of using a friction coefficient obtained on a wet road to determine the velocity of vehicle sliding in heavy rain, if in fact the friction coefficient actually increased due to the wedge, could be up to 5 km/h.
Speed of vehicle sliding for 30.0 metres on wet road

\[ \text{Speed} = \sqrt{254 \times d \times f} \]

Where: 254 is constant in all speed calculations for skid to stop

d = distance in metres

f = friction

\[ \text{Speed} = \sqrt{254 \times 30 \times 0.709} \]

\[ \text{Speed} = 73.5 \text{ km/h} \]

Speed of vehicle sliding for 30.0 metres in heavy rainfall

\[ \text{Speed} = \sqrt{254 \times d \times f} \]

\[ \text{Speed} = \sqrt{254 \times 30 \times 0.816} \]

\[ \text{Speed} = 78.8 \text{ km/h} \]
If the sliding distance was double at 60.0 metres then the effect of using a friction coefficient obtained in wet conditions when it would be likely that friction coefficient was increased due to heavy rainfall, then the affect could be as much as 8 km/h. In comparison to the effects of temperature, the effect is small and whilst using the friction coefficient, which has been obtained on a wet road, a collision reconstructionist can be sure that the velocity, which is being analysed, is not an overestimate. That is any calculated velocity would not be higher that the true speed that the vehicle was travelling. When a vehicle velocity is being presented in a court of law to prove or disprove the commission of a criminal offence, the most important consideration is that any vehicle velocity estimate is not higher than the true velocity. Although using a friction coefficient obtained on a wet surface to calculate the velocity of a vehicle sliding in a period of heavy rain is likely to result in an underestimate of speed, the margin of error is likely to be less than 7%. Given that it is impossible to determine the exact friction coefficient relative to any raining period with confidence, it is advisable to use wet friction rather than dry friction to ensure there is no possibility of providing an overestimate.

It is evident that the depth of any lubricant layer is the most relevant factor in determining whether the friction coefficient between car tyres and road surfaces may actually be higher in periods of rainfall compared to dry
friction. In periods of heavy rain the friction coefficient between car tyres and road surfaces is likely to increase. These results are surface specific to pneumatic tyres and bitumen road surfaces and without further research with other surfaces specifically, these results cannot be attributed to give similar results for other surfaces or objects. The viscoelastic properties of rubber make this substance unique and any behaviours observed can not reasonably be connected to other substances without further research. Furthermore, when considering wet friction relative to car tyres and road surfaces, consideration must be given to the fact that both tyres and road surfaces are designed to dissipate water. The results observed in this research are surface specific.

In heavy rain the friction coefficient between car tyres and road surfaces increased when the vehicle was travelling at about 60 km/h at the commencement of sliding. The phenomenon of hydroplaning is more likely to occur as speed increases, tyre tread depth decreases and water depth increases. Hydroplaning is defined as friction coefficients at or below approximately -0.10 g and essentially the surface of the tyre loses complete contact with the surface of the road due to the layer of water between the two. Essentially the wedge of water, which has failed to dissipate, and increases the force against the tyre, provides a ramp upon which the tyre can ride before continuing on top of the water (Fig 6.14).
Wheel lock up typically occurs as a result of severe braking. During wheel lock up, a driver may lose steering control and the friction coefficient is greatly reduced. A moving vehicle usually has a vehicle velocity which is equal to wheel velocity. The speed of a vehicle can be calculated by measuring the speed of wheel rotating and multiplying it by the nominal wheel radius. When a wheel becomes locked and slips, the vehicle velocity and wheel velocity will no longer be equal. Slip is a term commonly used to indicate the difference between wheel velocity and vehicle velocity.

\[ \text{Slip} = 1 - \frac{\omega R}{V} \]

*Where: \( V = \text{vehicle velocity} \)*

\( \omega = \text{wheel velocity} \)

\( R = \text{radius of wheel and tyre} \)
When a wheel is not locked or under braking then slip = 0. In the incidence of severe braking likely to result in lock up $\omega = 0$ whilst slip = 1. There will be an optimum slip value between 0 and 1. That is a value where the friction coefficient is at maximum. Maximum or peak friction coefficient during braking is typically recorded immediately prior to lock up. It is likely that when a vehicle is sliding in deep water peak friction is likely to be observed immediately prior to hydroplaning. Whilst assuming a friction coefficient of -0.1 or less when a vehicle is hydroplaning it is likely that deceleration will have occurred prior to hydroplaning.

The friction theories of Amonton, Coulomb, Bowden and Tabor have dominated all others for many decades. However, the large variations in experimental values suggest that adhesion theory does not fully account for the phenomenon. In 1981 Suh suggested that there are three mechanisms involved in friction. Namely adhesion, asperity deformation and plowing. According to Suh, frictional force is largely dependent upon plowing of surface asperities.

Plowing friction may be relevant to a soft wheel or tyre which can be easily deformed or alternatively when the ground upon which it is sliding is relatively soft. When a wheel sinks into the soft material and pushes or
plows its way through, this becomes the major source of friction. Plowing is the likely explanation for the increase in friction coefficient when a vehicle slides across a road in heavy rainfall. This further supports the theory that maximum of peak friction will occur immediately prior to hydroplaning. Whilst plowing force can be calculated, it is necessary to know the depth of the soft surface, which is simply not possible when analysing a collision, which has already occurred.

When a tyre slides on a road surface in heavy rain, the friction coefficient will be higher compared to a dry or wet surface. It is not possible to quantify the effect without determining the depth of the water, the tread depth of the tyre and the road surface composition. When analysing a motor vehicle collision, which has occurred in periods of heavy rain, it is recommended that a ‘wet’ friction coefficient test is performed to determine the friction coefficient relevant to the collision. However, this will certainly result in an underestimate of velocity. Although the friction coefficient in heavy rain may be higher than dry friction, it is possible that efficiency of dissipation may have been high and any plowing effect minimal. The rate of dissipation can not be quantified. By using a friction coefficient determined on a ‘wet’ but not raining road, there should be no risk of over estimating the velocity of a vehicle at the time of a collision. A friction
coefficient determined on a wet road should not be lowered further to account for periods of heavy rainfall.

6.6 FUTURE RESEARCH

Based on the earlier related laboratory research by Blythe and Seguin, which studied the effect of water depth on the friction coefficient of car tyres and road surfaces, it would be beneficial to research the effect of vehicle velocity in heavy rainfall conditions in real world environments. The work of Blythe would suggest that despite the friction coefficient being higher in rainfall, ideally knowing the water depth could also strengthen the validation of these results. However, it is difficult to determine such measurement in moving vehicles whilst maintaining conditions expected in periods of high rainfall. The ability to determine the actual water depth would be advantageous and may be an area of consideration for future research.
7. CONCLUSION

7.1 INTRODUCTION

The study was set out to explore the effects of vehicle velocity, temperature and rainfall on the friction coefficient of pneumatic tyres and bitumen road surfaces and has identified that all three elements will impact the friction coefficient between the two surfaces. The study also sought to identify whether friction coefficient of pneumatic tyres and road surfaces could be predicted to account for the effects of the three variables. The general theoretical literature on the subject area of friction and how it is affected by velocity, temperature and rainfall, specifically in relation to pneumatic tyres, is inconclusive within the diversification discourse. The study sought to answer four questions:

1. Is the friction coefficient of pneumatic tyres and bitumen road surfaces affected by velocity?
2. Is the friction coefficient of pneumatic tyres and bitumen road surfaces affected by temperature?
3. Is the friction coefficient of pneumatic tyres and bitumen road surfaces affected by rainfall?
4. Can friction coefficient of pneumatic tyres and bitumen road surfaces be predicted to account for any effect due to velocity, temperature or rainfall?

The main experimental findings are chapter specific and were each summarised within the respective chapter: Chapter 4: Vehicle Velocity and its Effect on Friction, Chapter 5: Ambient Temperature and its Effect on Friction and Chapter 6: Rainfall and its Effect on Friction.

7.2 EXPERIMENTAL FINDINGS

Vehicle velocity, ambient temperature and rainfall were all determined to affect the friction coefficient of pneumatic tyres and bitumen road surfaces.

1. Is the friction coefficient of pneumatic tyres and bitumen road surfaces affected by velocity?

The velocity that a vehicle is travelling when it commences to slide on a bitumen road surface will affect the friction coefficient between the tyres and the road surface. The effect will depend upon whether the vehicle is sliding with or without ABS braking. When a vehicle is sliding under the
affects of ABS braking the friction coefficient will decrease between 30 km/h and 40 km/h and then increase from 40 km/h to where it begins to plateau around 80 km/h. When a vehicle is sliding without ABS the friction coefficient will increase if the vehicle is travelling between 30 km/h and 40 km/h before then commencing to decrease until around 80 km/h where it begins to plateau.

2. **Is the friction coefficient of pneumatic tyres and bitumen road surfaces affected by temperature?**

The ambient temperature will affect the friction coefficient of pneumatic tyres sliding on bitumen road surfaces. As the ambient temperature increases the friction coefficient of the two sliding surfaces will increase. Between 3°C and 43°C the effect is positive and linear with a very strong correlation. No plateau was observed between the experimental temperature range.

3. **Is the friction coefficient of pneumatic tyres and bitumen road surfaces affected by rainfall?**

When a vehicle slides on a wet road the friction coefficient between the pneumatic tyres and the bitumen road surface will be lower when compared to the same tyres sliding on the same road surface when dry. However, when the same vehicle slides during a period of rainfall the
friction coefficient of the tyres sliding on the road surfaces will be higher compared to both the wet and dry road surface. The extent of the effect will be affected by the depth of the water layer forward of the sliding tyre. The volume of rainfall and the ability of both the tyres and the road surface to dissipate the water will affect the depth of the water. The greater the depth of the water layers the higher the friction coefficient between the tyre and the road surface.

4. Can friction coefficient of pneumatic tyres and bitumen road surfaces be predicted to account for any effect due to velocity, temperature or rainfall?

The friction coefficient of pneumatic tyres and bitumen road surfaces can be predicted using the MEHEGAN prediction model to account for the effects of vehicle velocity. When the friction coefficient of a sliding tyre on a road surface is determined using a vehicle which is travelling at a speed higher or lower than the speed of a vehicle being analysed then the MEHEGAN prediction model can be used to predict the friction coefficient relevant to the vehicle being analysed using the friction coefficient determined at a different velocity. This allows skid resistance tests to be conducted and safe speeds even when analysing the travelling velocity of vehicles involved in collisions or incidents and much higher speeds.
The friction coefficient of pneumatic tyres and bitumen road surfaces can also be predicted using the HARTMAN prediction model to account for the effects of ambient temperature. When there is a change in temperature between the time of a collision and the time of subsequent skid resistance temperature then it is likely that there will be a change in ambient velocity. The HARTMAN prediction model can be used to prediction the friction coefficient of pneumatic tyres sliding on bitumen road surfaces for any ambient temperatures higher or lower.

Using experimental testing of actual cars sliding on road surfaces it is not possible to quantify the depth of water forward of the sliding tyre. Therefore it is not possible to develop a model to facilitate the prediction of friction coefficient based on water depth. Whilst the experimental results identify that the greater the depth of water layer the higher the friction coefficient between the two sliding surfaces it is not possible to quantify the effect.

7.3 THEORETICAL IMPLICATION

The theoretical cases for modification needs to be reconsidered to further appreciate and recognise the affect of vehicle velocity, ambient
temperature and rainfall on the friction coefficient of pneumatic tyres and road surfaces.

The laws of friction are not relevant to the friction coefficient of pneumatic tyres and bitumen road surfaces. The experimental result of a sliding tyre without ABS is generally consistent with the suggestions of Takadoum (1997) in that the friction coefficient decreases with increasing speed. The velocity thresholds contradict the work of Heinrichs, Lloyd and Allin (2004). Whilst the pattern is consistent with most work presented since 2000 there is a need for further examination of minimum and maximum thresholds. The framework suggests strongly that friction coefficient of pneumatic tyres and bitumen road surfaces will decrease with increasing velocity.

The William Landel Ferry Theory already suggested that the friction coefficient of rubber and bitumen surfaces is affected by temperature which is supported by the experimental data. As recent as 2007 Takadoum indicated that as temperature increased the friction coefficient of the two surfaces would increase only to the surface reaches maximum softening at which point the surface friction coefficient will begin to decrease. The research considered ambient temperatures up to 43°C and no decrease in friction was observed. It is noted from the study that in Australian conditions there is no evidence to support the likelihood that
there will be ambient temperatures observed which would result in maximum softening resulting in a decrease in friction coefficient. Whilst conditions above 43°C do occur it is not a common phenomenon over a sustained period of time and occurs seldom. There is no evidence to suggest when maximum softening will occur for pneumatic tyres and bitumen road surfaces. There was evidence that skid resistance tests performed in quick succession will result in a reduction in friction coefficient. This is likely the result of heating of the vehicle braking components as opposed a reduction of friction coefficient between the tyre and the road surface.

The experimental findings relating to rainfall are significant when considered in conjunction with the laboratory research of Blythe (2013). The outline of the work of Blythe is that as water depth in the path of a sliding tyre on a road surface the friction coefficient will increase. The empirical findings of Blythe are essentially the same as this study and the research was performed over a similar time period, each without the knowledge of the other. The work of Blythe was performed in controlled laboratory circumstances and yielded the same findings as this study in real world testing. Both these two studies highlight the necessity for the realisation that the simple presence of a lubricant is not sufficient to confirm a reduction in friction coefficient. This work supports significant
early research that dry friction is higher than wet friction where there is no substantial depth to the lubricant layer.

7.4 IMPLICATION OF PREDICTION MODEL

The use of the MEHEGAN prediction model to predict the friction coefficient is a valid method for prediction friction between pneumatic tyres and bitumen road surface. This model was developed surface specific. It is reliable for predicting friction for any vehicle velocity using a known vehicle velocity between 40 km/h and 80 km/h. Whilst the method is both valid and reliable the effect when the friction coefficient is being determined for the use in vehicle speed reconstruction is very minor and not necessary when the speed being analysed is higher than the speed at which the test skid was performed. Any speed determination is likely to result in a further underestimation of the true speed of the vehicle. This is due to any speed calculation being based upon physical evidence of tyre marks which will already result in a speed under estimation.

The use of the HARTMAN prediction model to predict friction coefficient is both a valid and important model to be considered when contemplating the friction coefficient of pneumatic tyres and bitumen road surfaces at a
range of ambient temperatures. The effect of temperature on the friction coefficient of pneumatic tyres and bitumen road surfaces is significant. Where a vehicle speed is being analysed using a friction coefficient determined in different temperature conditions the HARTMAN prediction model should be used to predict the actual friction relevant to the conditions which were occurring at the time which is being analysed. All collision reconstructionists should consider the use of the HARTMAN prediction model in any speed analysis. The model is validated for ambient temperatures between 3°C and 43°C.

7.5 RECOMMENDATION FOR FUTURE RESEARCH

The scale of debate relating to this research and findings is complicated and multifaceted. The further validate the findings of this research achieve solid understanding of the effects of velocity, temperature and rainfall more case studies and research needs to be performed specifically relating to pneumatic tyres and bitumen road surfaces in controlled laboratory conditions.
The effects of velocity need to be considered and examined at speeds above 80 km/h. Ideally for collision reconstruction purposes velocity analysis up to 160 km/h would be ideal. Safety is likely to prove the most significant obstacle as higher velocities are examined.

The effect of ambient temperature was examined extensively but did not extend to temperatures below zero. Whilst it would be expected that friction coefficient will continue to decrease as the ambient temperature continues to decrease, it is not possible to validate the use of the HARTMAN prediction model without such research.

Development of a prediction model to account for the effects of rainfall would require an ability to measure rainfall and quantify water depth. There are a multitude of parameters and it would be difficult to perform in real world testing. Whilst laboratory testing should be able to identify the minimum and maximum thresholds in relation to water depth it is likely to be difficult to attribute this relationship to rainfall due to the inability to quantify the exact rainfall conditions that were occurring at the time of a collision.
7.6 DEDUCTION

In spite of what is often reported in relation to the phenomenon of friction, it is possible to predict friction. The friction coefficient of two surfaces is specific to the two surfaces in contact and conclusions cannot be drawn from the results of two sliding surfaces and attributed to two different sliding surfaces. The friction coefficient of pneumatic tyres and bitumen road surfaces is affected by velocity, temperature and rainfall. Using a known friction coefficient for a specific tyre and road surface it is possible to accurately predict the friction coefficient of the same tyre and road surface for a range of velocities and temperatures.
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