DYNAMIC DRIVER WORKLOAD ASSESSMENT AND ITS
IMPLICATIONS FOR HIGHWAY DESIGN AND OPERATIONS

by

PATRICK TAMBA MUSA

B. Eng. Hons. (Civil), Fourah Bay College, University of Sierra Leone, 1987
M. Sc. (Highway Engineering), University of Birmingham, UK, 1992

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

THE FACULTY OF GRADUATE STUDIES

Department of Civil Engineering

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

December 2003

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Design standard manuals and road safety guidelines are all formulated with safety as the main cornerstone, but road mishaps have continued to occur with the dire consequences of loss of life and serious injury. Research has shown that a large proportion of these mishaps can be attributed to the driver, thereby increasing the need for the application of human factors in road design.

It is now generally accepted that to build safer roads, design should reflect the behaviour and the characteristics of the driver. Research in this area has identified design practices that tend to overload the information processing capacity of the driver as the main cause for concern. These practices often lead to high mental workload and subsequent driving errors.

The engineer therefore needs to predict driver workload in order to design and operate a road system that will accommodate the information processing capability of the driver. This research proposed a driver workload model that combines road complexity and operating speed in a time constraint approach to workload. The model was tested in an experiment on a test track consisting of curves of various radii, interspersed with tangents. Twenty four (24) drivers drove the test track in an instrumented car, at speeds ranging from 30km/hr to 100km/hr, as well as speeds mimicking driving scenarios adopted by late and leisure drivers. The workload experienced by drivers was measured using a secondary task technique of random number repetition.
Amongst other things, the results showed that whilst satisfying their motives, drivers aspire to optimum workload levels which are governed by their speed management strategies, and that by modelling these strategies, design workload limits can be determined. In the experiment, late drivers adopted a speed management strategy that limited the demand on their attention (workload) to 80%. Leisure drivers had an attention demand limit of 45%, whilst the 85th percentile driver on the road showed a limit of about 50%.

The above limits were used to evaluate the experimental test track. The results were comparable to those from the accepted geometric design consistency evaluation criteria.
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ACKNOWLEDGEMENT

The financial support for this research came from NSERC operating grant of my supervisor Dr. Frank Navin. The sources of these funds are acknowledged with special thanks.

I would like to express my sincere gratitude to my supervisor, Professor Navin, for his guidance and support (technical and moral), as well as the invaluable advice in the course of this research. His ideas for a more inclusive consideration of the driver in geometric were very useful in shaping this research.

I would also like to thank Dr. Tarek Sayed who gave advice and comments on contents of the research as it progressed. His guidance especially during Dr. Navin’s one year of sabbatical was very helpful.

Dr. Bill Mercer (Applied Research & Evaluation Services, UBC) also gave very useful advice on the experiment, structure of the research, and thesis. His contribution is appreciated with thanks.

Special thanks go to the team that made the experimental part of this research a success. The contributions of Mr. Randy Burg, P. Eng of Innovative Vehicle Testing (IVT) and Mr. Craig Navin were very useful in this regard. I also wish to acknowledge the drivers who volunteered to participate in the experiment.
The use of the Boundary Bay test facility was courtesy of the Justice Institute of British and the Royal Canadian Mounted Police, E Divisions. I thank them for giving me the opportunity to use their facility.

This work is dedicated to my mother Sia Nanah, whose memory kept me going over the years.
CHAPTER 1

INTRODUCTION

More than one million people are killed every year around the World, and 10 million more injured in road crashes (World Bank, 2003). In 2001, 2,778 people were killed on Canadian roads, and another 221,158 injured in 151,835 road crashes (Transport Canada, 2003). This equates to 8 deaths, 600 injuries, as a result of some 420 road crashes every day in Canada. An ailment that causes so much sudden trauma should be considered a national epidemic. The economic implications are enormous, being the equivalent to 1-3% of a country's Gross National Product (World Bank, 2003). The total cost of road crashes to the Canadian economy is estimated at about $25 billion annually (Transport Canada, 2003). Developed countries are reducing the deaths and injuries on their roads, but the worldwide trend in accident statistics is not encouraging (World Bank, 2003). According to a WHO/World Bank/Harvard University study, road crashes will rank as the third leading cause of death and disability by the year 2020, compared to the rank of 9th in 1990 (Murray et al, 1996).

Road safety improvement techniques have targeted the causal factors of crashes:

- the road environment (design)
- the road user (mainly the driver)
- and the vehicle

Crashes result from any one or a combination of these three components of the highway system. Studies by Sayed et al. (1995) into the causal factors of crashes have identified
the driver to be a contributing factor for more than 90% of the mishaps on the road. The distribution of collision causal factors is similar for Canada (Sayed et al., 1995), USA (Treat, 1980), and UK (Sabey et al., 1980). It therefore seems reasonable to concentrate on the driver in order to make a meaningful impact on road safety. Highway safety design should make driver behaviour and characteristics the basic elements for designing the features that are seen on the road. Traditional road design, however, deals mainly with vehicle and road mechanics. The basic safety assumption is, as long as the dynamics of vehicle movement are satisfied, design is assumed to be safe. It is now generally accepted that this is not the case. In response the current move towards “flexible” design standards that accommodate Road Safety Audits and Design Consistency evaluations is a move to build explicit safety into the design.

This research looks at a more inclusive approach to road design, with the driver as the basic element of design. When designing good highways one must consider how people drive vehicles. One basic formulation of driving is given by car following models (see May (1990), and Figure 1.1). In these models, a driver’s reaction (accelerating or decelerating) is the product of a stimulus and the driver’s sensitivity. Drivers in car following models set their speed based on the spacing (gap) between the lead vehicle and themselves. Even for open highway driving by a single vehicle, the model still holds if a few changes are made. The driver now sets behaviour given the complex stimulus such as the design features of the road, road signs, and the environmental conditions. An understanding of the effect of this stimulus on the driver, and the way the driver behaves to stimulus, should explain how some failures occur on the road.
In the basic model in Figure 1.1, the driver receives stimulus (information) from the road environment and the vehicle, processes this information and then arrives at vehicle control decisions for the safe handling of the vehicle. Implicit to the model is the limited capacity of the driver to process information; too much information overloads the information processing capacity of the driver thereby resulting in high workloads. This research looks at the theory of Driver Workload as a means of incorporating driver behaviour into the road design process from first principles. The factors determining driver workload are investigated and used to develop a model that suits the driving situation to be used in the road design process.

![Driver Model Diagram](image)

Figure 1.1: Driver Model as a Single Processing Unit

### 1.1 BACKGROUND

Highway design is guided by standards that are incorporated in design manuals such as those developed by the Transportation Association of Canada (TAC, 1999), and for the United States, the American Association of States Highways and Transportation Officials.
(AASHTO, 1994). Implicit in these manuals (and others) is an emphasis for safety since the design of the basic elements of the road system is geared towards safety. There are, however, some deficiencies that need to be addressed:

1. Safety considerations appear to be more concerned with driving dynamic safety (such as those related to skidding out on curves, rollover, and stopping sight distance deficiencies, etc). There is no way of knowing how various road features affect the perceptive and decision making capabilities of the driver.

2. The basic principle of these standards is the design speed concept, which allows the indiscriminate use of minimum, or absolute minimum values of design parameters with maximum values. This has been identified as the main cause of design inconsistency, leading to the violation of driver expectancy and high driver workloads (Kramme et al., 1992).

3. Although human factors account for more than 90% of road crashes, the main considerations of human factors are normally implemented after the design and are either based on expert opinion, as in safety audits, or empirical evidence as in design consistency evaluations.

4. Similar to the treatment of the effects of geometric design, there is no theoretical foundation for estimating the effects of in-vehicle information systems that are employed today in the name of safety and efficient use of the highway system.
Also, some other road design elements, whose parameters are not determined by design speed considerations (e.g., shoulder width/colour, lane drops, bridge widths, lane markings, etc), are designed based only on experience and empirical evidence.

There is a need for a design process, which takes into account the role the driver plays in the safety and operation of the road system. The consideration of human factors in highway design is growing; it is generally accepted now that the road should be built to reflect the needs of the driver (Kanellaidis, 1999). Human factors experts are, however, advocating for a theoretical approach, one that has a basis in human information processing theory (Hendy et al., 1997; Kantowitz, 1992). A close look at the driving task explains how this relates to what happens on the road. In order to move from one point to another, the driver collects information on the path ahead, makes decisions on the safe path to be followed, and takes control actions in a feedback manner (Figure 1.1). Complex road environments would therefore present more information-processing load on the driver. A fundamental aspect of the human information processing theory is that there is a limit to the amount of information that the human operator can process at any one time. Complex road situations would therefore result into high driver workloads.

Apart from complex road designs, the information content from traffic, traffic control devices, and in-vehicle information systems might sometimes present information processing problems to drivers, leading to increased driver workload.
The design process should be able to make accurate estimates of driver workload and be able to compare it with driver capabilities. However, because of the multi-faceted nature of workload, it has been hard to make deterministic measurements of workload. Some researchers (de Waard, 1996) have even argued against the comparison of measured workload with operator capacity to determine whether a critical point has been reached. One of the points put forward was that the limit for an elderly person would be different from that for a younger person. This is indeed true, and the concern is increasing as the number of elderly people in the society (especially industrialised) keeps on rising (Kanellaidis, 1999). Engineering solutions would therefore need to look at the demographics to decide where specialised treatment is required. The same argument may be put forward for the use of perception reaction time, which has been used in highway geometric design for ages. One solution may be to design for some percentile driver (e.g. the 85th percentile driver), or use reliability analysis (Navin, 1990; Navin et al., 1998) to decide on design parameters, so that the majority of the driving population is taken care of.

The multi-faceted nature of workload also means that any theory or model of workload should include the major determinants of workload in the development of the model. Workload measures can either show association, dissociation or insensitivity to various workload situations. It all depends on whether all the workload determinants are considered in the evaluation process. De Waard (1996) has reported on instances where driver workload measurements were found to be inconsistent with the situation.
1.2 AIMS AND OBJECTIVES

The aims of this research are as follows:

1. to investigate the various components of driver workload that could be used to develop a working model of driver workload,
2. to develop a model for estimating driver workload based on the major components of workload,
3. to use the model to show how design consistency arguments could be derived from driver workload theory,
4. to make suggestions for the application of the model in the design of in-vehicle information systems, and
5. to give recommendations on how workload theory could be combined with driving dynamic safety considerations to develop a more robust design model.

The final objective of the research is to provide the basis for the incorporation of driver behaviour into the design process. It is a pro-active design approach that looks at the effect of various design aspects on driver behaviour and makes adjustments to design parameters to accommodate the capabilities of a majority of drivers.

1.3 METHODOLOGY

The methodology used in this research is comprised of two parts: (1) a theoretical analysis of driver information processing as it relates to driver workload, and (2) an experimental investigation of the determinants of driver workload. The theoretical analysis looked into the literature to investigate the major determinants of driver
workload. An attempt was made to combine these workload determinants in a more robust driver workload model that should have a higher predictive power for driver workload assessment.

The experimental programme sets out to determine the effects of the various workload determinants in workload estimation. The experiment was conducted on a test track. Results from test track experiments have been found to have similarities to those on the road (Wooldridge et al., 2000). In any case, test track experiments should point in the same direction as to what happens in the real road situation. Since workload determinants are not supposed to act in isolation, the way they combine to effect experienced workload was also investigated in the experiment.

1.4 THEESIS STRUCTURE

This thesis is divided into two main sections, Section I, and Section II, as shown in Figure 1.2. Section I, the introductory section, has the first two chapters, with the rest of the chapters in Section II.

In the present chapter, the introduction, the road safety situation is presented with a brief description of the institutional framework that is a key to the road safety problem. With the problem thus defined, the aims and objectives of the research are presented, followed by the methodology adopted. In Chapter 2, the literature review, the design practices responsible for the road safety problems are highlighted and the trend towards a driver-centered road safety design is presented.
In Chapter 3, the general concept of mental workload is presented, together with measurement methods and some basic predictive models. This is followed in Chapter 4 with the application of the workload concept to the driving situation. Driver workload measurement techniques are presented and some of the reasons why these techniques might fail are discussed. Models that have been used so far to predict workload are presented and their merits in the prediction of driver workload are discussed. A model, which tries to capture the role of speed as an important component of driver workload is presented in Chapter 5. Speed is modeled both as variable, and as a major tool in behaviour adaptation. Chapter 6 describes a test track experiment used to test the model developed in Chapter 5. The results of the experiment are also presented and discussed in this chapter. In Chapter 7, the possible application of the workload model in geometric design and the design of in-vehicle information systems is discussed. The conclusions are presented in Chapter 8.
Section I

Problems
Important issues
The Future

Section II

Objective
Dynamic Design for Driver Capacity

Proactive Road Safety Design

Probability of Failure (Human Reliability) Driver Error Model

Mathematical Model based on Human Information processing Theory – Hendy’s Model

Capacity Condition RIP determined by 85th percentile driver

Demand Condition RID determined by speed/geometry

Components

RID = Bt * V_{85_t} = D bits/sec

RIP = B_s * V_{85_s} = C bits/sec

Reliability Analysis
Probability of Driver Failure P_t
P_t = Prob(RID, RIP > 0)
P_t = Prob(RID/RIP > 1)

Design Consistency Theory

Time Pressure TP
TP = T / T_s = V_s / V_t
TP = T_s / T_t = V_t / V_s
When V > V_s, Time Pressure = design inconsistency = errors

AMMEND STANDARDS
Advocate for relationship design practice in design standards

Driving Dynamic Safety (f_s, f_t)

Figure 1.2: Thesis Structure
CHAPTER 2
LITERATURE REVIEW

2.1 THE GEOMETRIC DESIGN PROCESS

Geometric Design is the process by which the physical features of the roadway, such as the horizontal and vertical alignment, roadway width, and intersections, are defined. The dimensions of these features vary from one road type to another, depending on the functional classification of the road. Functional classification groups roads into specific types, which affect their quality (number of lanes, minimum radius, maximum grades, etc). The group into which a particular road is designed depends on the function, i.e. whether it will serve through traffic, local traffic or whether it is a collector. It also depends on the traffic (volume and composition) that will use the road. These in turn determine the speed and flow characteristic expected on the road. A road with a high volume of traffic should move traffic faster and in an uninterrupted manner. Roads are further classified into urban or rural roads.

Once a road is classified into rural or urban, freeway, arterial, collector or local road, the operational standard is set. This then determines the controls that will affect the design. Major design controls include (AASHTO, 1994)

- design speed
- design vehicle
- traffic volume
- level of service
The design controls combine together to define the design elements of the road. They determine the minimum radius of horizontal curves, maximum grades, sight distances and roadway widths. The values of these elements account for the safe and efficient movement of traffic. Other controls that may affect these design elements include terrain, the environment and their economic consequences. Forcing the limiting values of design elements in some terrains, may result in high costs that affect the feasibility of the road project. Environmental controls may also mean that design standards can be met only at higher costs. Therefore highway design frequently involves reaching a compromise between safety, efficiency and economy (Kanellaidis, 1999), and this may not always lead to maximum safety.

2.2 DEVELOPMENT OF SAFETY IN THE HIGHWAY DESIGN PRACTICE

Safety on roads first became a serious concern with the increase in vehicle speeds as well as the number of vehicles (Lamm et al., 1999). One can only imagine how geometric design has evolved from the day the first self-propelled car was driven with a maximum speed of 2 mph in the mid 1700s to the present day car. Before the advent of fast automobiles, road design engineers were concerned about the geometry of the road for different reasons. For the vertical alignment, long steep grades were avoided mainly for economic reasons. The steeper the grade, the higher the operating cost, as more horsepower was required to haul freight by animal-drawn vehicles. In fact, the economic consequences of steeper grades were the most important consideration for road design. For horizontal alignment design, the concern was that long animal-drawn vehicles should be able to manoeuvre easily around curves (Wiley, 1928).
The early 1900’s saw a revolution in road design, as the safety aspects of high-speed automobiles became a concern. Flat grades were still required but this time for operational as well as safety considerations. Provision of adequate sight distance for the driver to stop in time in order to avoid hitting obstacles or other vehicles on the road became important for vertical alignment design. Passenger comfort as the vehicle traverses vertical curves was also an important consideration, a consideration brought about as a result of higher speeds. Road sections in horizontal curves now needed to be superelevated and limitations placed on minimum radii in order to accommodate the speeds safely without skidding. The evolution of the road design process has been well documented by Lamm et al (1999), whereby speed became a major design factor and the concept of design speed was borne with the view of achieving comfort and safety.

Design speed has been defined as “[t]he maximum safe speed that can be maintained over a specified section of the highway when conditions are so favourable that the design features of the highway govern” (AASHTO, 1994). It was on the principle of design speed that many design standards, based on safety and driving dynamics were developed in the early 1900s (Lamm et al, 1999). Once the design speed is chosen (depending on the road’s function, traffic volume and topography), the limiting values of the road design parameters (such as minimum horizontal curve radii, vertical curvature, grades, stopping sight distance) are determined, and safety is assumed to be built into the design.

The design speed is, however, the maximum speed for the most restrictive feature of the road section. This means that speeds higher than the design speed can be attained on less
restrictive sections (tangents), sometimes requiring significant speed reductions or critical driving manoeuvres in order to safely traverse succeeding road features that are designed with limiting values. A design requiring significant speed reductions and/or other critical driving manoeuvres is considered to be an inconsistent design (Al-Masaeid et al. 1995) and has been associated with accident experience on roads (Taylor et al. 1972, Thompson et al. 1983, Lamm et al. 1986).

Good design should be such that a driver anticipates the next road condition correctly and does not need to make any critical driving manoeuvres. The driver approaches each design feature with an anticipated action plan compatible with the speed and manoeuvre requirements of the feature; driver expectancy is not violated. Changes in design features should be introduced gradually so that the driver adapts speeds and actions accordingly for safe and efficient operation.

2.3 CURRENT DESIGN PRACTICE

The Design Speed Concept still remains important in many highway design standards. The design of a given road starts with the determination of the function it will serve society. Will it be a freeway, a collector or a local road; situated in an urban or rural setting? These attributes combine with the projected traffic volume and the terrain to specify the functional classification of the road. With the functional classification, the design speed is given, which then determines the quality of the road in terms of limiting values of the various design elements. Various road jurisdictions have compiled values of design elements into design standard manuals for easy use by design engineers. The
latest editions of these design standard manuals for Canada and the United States of America are the Manual of Geometric Design Standards for Canadian Roads and Streets (TAC, 1999) and A Policy on Geometric Design of Highways and Streets (AASHTO, 1994) respectively.

This concept of design has its advantages and disadvantages. The first advantage lies in the ease with which these manuals make highway design for the engineer. They are also good for administrative purposes because, once a road is classified and the design speed set, the level of government responsibility is determined. It is also assumed to provide for consistent design in that various features are designed to the same standard. The procedure leads to the efficient production and operation of highways.

There are however serious operational disadvantages of this design concept:

1. Although the design standards were compiled on driving dynamics and safety, there is no explicit consideration for safety, an aspect strongly criticized by Hauer (1988). He adds that, unlike structural and hydraulic engineers, the highway engineer cannot predict the safety consequences of his/her design because the design standards only address safety in a qualitative manner. The design standards should include charts, which show the number of accidents/severity for each design option and let the engineer make the decision about safety.
2. The design speed concept is the main cause of design inconsistency, even though it purports to support it. This was echoed by Leisch and Liesch (1977) as well as Anderson et al. (1999) as the main source of violation of driver expectancy. The method of dealing with inconsistency is mostly through iterative methods. The road is designed according to the design speed criterion; it is checked to locate sections that might exhibit inconsistencies, and adjustments made in design parameters to improve consistency (Lamm et al., 1999).

2.4 GEOMETRIC DESIGN AND HIGHWAY SAFETY

It is generally accepted that the way a road is built affects its safety. Two-lane rural roads account for 50% of highway fatalities, and half of these fatalities occur on curved sections (Lamm et al. 1992). Compared to interstate highways, the fatal and injury vehicle-mile exposure accident rate on two-lane rural roads is four times higher (Cleveland et al., 1984). The fact that interstate highways are more generously designed with flatter curves, wider cross-sections, and longer sight distances accounts for this marked difference in safety (Cleveland et al., 1984) which supports the assertion that a road can be built safer. Specific studies have looked at the effects of highway geometric design elements such as road cross-section, vertical and horizontal curvature, sight distance, and intersection parameters on accident occurrence.

Studies by Pignatario (1973), Silyanov (1973) (based on data from Russia and Germany), and Zeeger et al (1988, and 1994) showed that accident frequency reduces with increase in road cross-sectional width. On the relationship between accidents and horizontal curve
design, various studies have shown that accident rate increases with increase in curvature represented by the degree of curve (D). Mathews and Barnes (1982) developed a relationship of the form:

\[ \text{Accidents/MVK} = 0.071 \times D^{0.64} \]  \hspace{1cm} (2.1)

where MKV = million vehicle kilometers

\[ D = \text{degree of curve} \]

In another study based on data from New York State, Lamm et al. (1988) derived a multivariate relationship of the form:

\[ \text{Accidents/MVK} = -0.88 + 1.41D \] for \( 1^\circ < D < 26.9^\circ \)  \hspace{1cm} (2.2)

According to Lamm et al. (1999), Hoffman investigated the first accident situation on German autobahns (interstates) in 1943 in which he pointed out the importance of long steep grades to highway safety. Recent studies (Choueiri et al. 1994) have confirmed that accident rates generally increase with increase in grade. In a study to quantify the accident potential of road geometrics, the Federal Highway Administration (FHWA, 2000) developed accident modification factors for grades that indicate a 1.6 % increase in accidents for every 1% increase in grade.
Despite the above evidence, highway engineers have not been able to predict the safety consequences of their designs with any precision. Several factors may be responsible for this:

1. Accidents have to occur before the relationship between their occurrence and various geometric features can be established. Accidents are however such a rare phenomena that available data are often sparse.

2. The recording of accident data is often not precise both in terms of the number of accidents or the location. The probability of an accident being recorded increases with the severity. In terms of the location, a crash vehicle location may not necessarily be in a position where the events leading to a crash originated.

3. Crashes occur as a result of a combination of various road design features and driver behaviour, and it has not been easy to isolate the contribution of the various factors.

As a matter of fact, a major proportion of road crashes, which are attributable to design, occur as a result of the driver's failure to interact with the design of the road (Figure 2.1). In other words, road design does not act in isolation to bring about accidents as would normally occur in the case of structural or geotechnical engineering failures. A separate assessment of human reliability may be required in order to determine the reliability of the total road system with any precision.
2.5 HUMAN FACTORS AND HIGHWAY DESIGN

The success of any facility designed to be used by humans depends to a large extent on the ease with which users can utilize the facility. Before the Second World War, it was expected that humans should adapt to tasks imposed by system design. The rapid increase in technology (especially in aviation and other military equipment design during World War II) and the information needs that accompanied this increase changed that perspective. It became accepted that, for man-machine systems to function efficiently in an error free manner, system tasks should be adapted to the limitations and capabilities of the people who will use them. The subject of Human Factors, or Human Engineering, or Ergonomics became an important phenomenon as a result (Sanders et al., 1993).

Human Factors can simply be defined as 'the design of man-machine-environment systems to suit the capabilities of the people who will use them' (Forbes, 1972). The basic approach to human factors design has been outlined by Forbes (1972) to be as follows:

1. Analysis of the tasks required by the system.
2. Measurement of the abilities of operators who will form the human part of the system.
3. Analysis of the most likely errors.
4. Design or modify the system to fit the abilities and limitations of a majority of the operators.
5. Train people to operate the system.
The need for human factors in highway design can be traced as far back as the early 1930's when data on human characteristics/behaviour was developed to aid traffic engineers to provide facilities fitting the needs and abilities of motorists. The various researches on driver characteristics and behaviour starting from 1927 to 1955 have been well documented by Forbes (1972). It was clear from these early studies that errors, lapses, and limitations of the road user accounted for 75 to 90 percent of the mishaps on our road systems.

To date, human factors remain a major concern in highway safety research. Recent studies in the US by Treat (1980), in the UK by Sabey et al. (1980), and Canada by Sayed et al. (1995) into the causal factors of crashes have identified the driver to be the contributing factor for more that 90% of the mishaps on the road (Figure 2.1). These mishaps have been associated with errors, lapses and limitations of the driver.

![Figure 2.1: Accident contributing factors.](image)
The driver's contribution to mishaps on the road can be divided into two main areas: (1) road design-related errors, and (2) non road design-related errors. Design-related errors are those dealing with the effect of highway geometric design on driver behaviour, whilst non design-related errors are those associated with licensing, education/training, and enforcement. Lunenfeld (1993) argues that there is little road design can do to eliminate non road-design related errors (although one can argue that design practices like Forgiving Highways can reduce the effect of these errors), but that design-related errors can be dealt with and everything should be done to eliminate them.

The past half a century or so of modern road building has seen much progress in the understanding of the application of the general human factors approach to road design. Road safety practitioners are fully aware of the fact that road safety highly depends on their understanding of driver behaviour/characteristics, and they sought to design roads that adapt to driver attributes (Lunenfeld, 1993; Kanellaidis et al., 1997). Hubert (1992) pointed out that the human element of any system is largely "given", and that the other elements must be designed and operated around the human element. The key areas of design concern that have a direct bearing to human factors include (Alexander et al., 1985):

- Situations that violate driver expectancy,
- Situations that place too much demand on drivers,
- Situations that put too little demand on drivers causing lack of vigilance and,
- Information deficiencies.
All the above concerns relate to how the driver perceives information from the vehicle and the road environment in particular, and how this information is processed to arrive at meaningful control actions. The information content and the manner in which the information is presented can be key determinants of successful information processing.

2.5.1 The Driving Task and Information Handling

To drive a vehicle in an error-free manner, the driver collects information from the road, the vehicle, and the environment. About 90% of the driver's information need is collected visually (Alexander et al., 1985), with some being collected via auditory (e.g., engine sound, horns and sirens) and other sensory inputs. For instantaneous driving movement from Position A to Position B, the driver collects information regarding the present position, the course and the speed of the vehicle relative to obstacles in the road system. These obstacles may include other vehicles, pedestrians, and restrictions due to the road layout. Information is then collected about the road ahead and estimates are made concerning the position of the other obstacles in the next instant. The driver will then make control decisions on course and speed in order to be in Position B in the next instant without any incidents.

The accuracy of information collected, the driver's state of alertness (e.g., fatigued, drugged, etc.), and the long-term experience work together for the driver to make correct estimates and decisions. Information needs sometimes compete, requiring the driver to prioritise among the various needs. The driver is thus in a constant state of search for information, information processing, and decision making (Alexander et al., 1985).
2.5.2 Perception Reaction Time (PRT)

The time taken by the driver to perceive information, process it, and respond is the perception reaction time (PRT). Perception reaction time varies from one person to another as a result of variability in drivers as human beings, or because of the state of the driver (e.g., fatigued, alcohol, etc). PRT also varies according to decision complexity, content of information, and expectancy. Johannsen et al. (1971) measured brake reaction time for expected and unexpected signals. In expected situations, brake reaction time averaged about 0.66 seconds, with a range of 0.2 seconds to 2.0 seconds.

![Graph showing median driver reaction time expected and unexpected information](Figure 2.2: Median Driver Reaction Time Expected and Unexpected Information (AASTO, 1994))

(AASTO, 1994)
With unexpected signals, reaction times increased by 35%, with some drivers taking over 2.7 seconds to respond. A complex decision with several alternatives may take several seconds longer than a simple decision. The longer the reaction time required, the less time available for the driver to attend to other information needs that may arise; this leads to vital information being missed thus resulting in errors.

2.5.3 Driver Expectancy

Alexander et al. (1985) defined driver expectancy as relating to a driver’s readiness to respond to situations, events, and information in predictable and successful ways. It affects the speed and accuracy of driver performance and is therefore a major consideration for the application of human factors in the design and operation of the road system. Design features that conform to driver expectancy increase the driver’s readiness to perform a driving task, resulting in fewer errors. Driver expectancy is relevant for all aspects of the driving task; from vehicle handling to lane tracking, hazard avoidance, and trip planning, for example.

Two forms of driver expectancy have been defined (Alexander et al., 1985); a priori and ad hoc expectancies. A priori expectancy is long-term expectancy which the driver develops from years of driving experience and brings to the driving task. People get used to the way things are normally designed or presented to them so that any deviation from the norms can lead to delayed response or serious consequences. For example the ON position for a light switch in North America is UP whilst it is DOWN in Europe. A European on a first visit to North America cannot be expected to turn lights ON and OFF in an error free manner. Similarly, there are certain design aspects in driving that come to
be expected, and any deviations from these norms will result in driving errors. Freeway exits will normally be expected on the right hand side of the road, and if for some reason one is placed on the left, the likelihood that drivers will miss the exit increases. Other examples of *a priori* expectancy may include; a single lane bridge on a two-lane road or an intersection hidden by a crest curve.

*Ad hoc* expectancy on the other hand is the expectancy which the driver picks up on a particular trip and is therefore short term expectancy. As a driver goes through the first few kilometres on a road, certain road features are met that make the driver build up expectancies for downstream features. Any abrupt changes in downstream features would be a violation of a driver's *ad hoc* expectancy and the effect would be drastic for the unfamiliar driver.

2.5.4 Design Consistency

Design consistency has been defined as the extent to which the road is designed to avoid critical (difficult) driving manoeuvres and ensure safe operations (Al-Masaeid et al. 1995). Anderson et al. (1999) defined geometric design consistency as the ability of the road’s geometry to conform to driver expectancy, stressing that fewer errors are made in the vicinity of geometric features that conform to driver expectancy and vice versa for those that do not conform to driver expectancy. Lack of geometric design consistency; a feature of rural two-lane highways is thus considered a major source of violation of driver expectancy (Anderson et al., 1999; Kanellaidis et al., 1997).
Kanellaidis et al. (1997) have listed the following design practices as being, among others, the main contributors to design inconsistency:

1. The evolutionary changes in design guidelines (e.g., in the case of adjacent sections of a highway system built at different times).
2. The wide range of design values allowed by design standards as a result of the design speed concept.
3. Arbitrary decisions regarding the termination or streamlining of highway construction projects without adequate transitions.
4. The fact that the design speed concept is applicable to the design of horizontal and vertical curves, but not to the design of tangents.

What the above have in common is that the driver is able to operate at high speeds on some sections, thus giving the expectancy that this standard continues. Often large speed reductions and/or critical driving manoeuvres are required on downstream sections that were designed to the applicable design speed. According to Krammes et al. (1992),

“Theoretically, the only way the design-speed concept could systematically prevent inconsistent operating speed patterns is if one presumes that the drivers know the design speed and choose an appropriate operating speed less than or equal to the design speed, even though it may be safe to operate at higher speeds along most of the alignment. Clearly this assumption is unreasonable.” (Krammes et al., 1992, 2)
Harmonizing design speed with operating speed and/or harmonizing operating speeds between successive design elements has been recognized by many jurisdictions as a remedy for design inconsistency. By 1943, design consistency was already a concern in Germany and was reflected in design guidelines (Lamm et al., 1999). Today, German design guidelines have the most quantitative requirements aimed at improving design consistency. The requirements are as follows

- The difference between the 85th percentile speed ($V_{85}$) for two successive sections should not be more than 10km/hr for good design practice.
- Minimum radii are specified for tangent-curve combinations
- Maximum and minimum tangent lengths are also specified.

The Swedish guidelines also have restrictions on minimum and maximum tangents and they also predict operating speeds in order to determine design consistency (Krammes et al., 1992). The French policy also has restrictions on maximum tangent length (Lamm et al., 1988). In Britain however, design inconsistency is tolerated when avoidance affects costs and the environment severely (Kanellaidis et al., 1997).

In North America, the need for consistent design has been acknowledged and efforts are being made for its adoption, but what appears in the design standards is mostly qualitative. The Canadian standards (TAC, 1999) advocate for the following:

- Sharp curves are to be avoided after long tangents, and
- Sudden changes in radii between successive horizontal curves are to be avoided.

In the U.S guidelines (AASHTO, 1994), the section on “General controls for Horizontal Alignment” makes the following recommendations
• The ratio of successive radii of compound curves should not exceed 1.5:1, and
• Sharp curves should not be introduced after long tangents.

The maximum curvature based on design speed should only be used in the most critical condition.

2.6 ROAD SAFETY RELATED DESIGN

Road design is to a large extent a compromise between a number of factors, which include safety, economy, mobility, and environmental considerations. Whilst most of these factors are quantifiable, safety is yet to be accurately quantified, which according to Hauer (1988), leaves safety to be determined by default.

Ideally, the road safety engineer needs to predict the safety performance of one design as compared to another, not in a qualitative manner, but in a quantitative one. Only then can the engineer justify expenditures made in the name of safety. Safety needs to be predicted in highway design as it is done in structural as well as in geotechnical engineering. Navin et al. (1999) point out that non-technical people have been able to challenge highway safety practices because safety estimation is highly dependent on "common sense". To change this trend, highway safety has to be "knowledge-based" as argued by Hauer (1988) and Navin et al. (1999). The road safety engineer has to be able to estimate safety from first principles, which requires knowledge about the mechanisms of accident causation. In this regard, Viner and English agree that:

"An important landmark is reached in the evolution of a scientific field when classification of its subject matter is based on the relevant, fundamental processes
involved rather than on descriptions of the appearances of the phenomenon of interest..." (Viner and English, 1995)

It was based on this approach that Viner and English (1995) tried to develop risk engineering models applicable to road safety. The goal was to identify the basic mechanisms and outcomes associated with major road events, and find the probability of all mechanisms and outcomes in order to arrive at an estimate of risk in the road system. They argued that prevention should be based on taking steps to influence the occurrence process by modifying any of the factors which affect the probability of occurrence, and the consequence or exposure to the circumstances in which they occur; this is only possible when these processes or mechanisms are well understood.

An event can be produced by a combination of several mechanisms, and can lead to different outcomes, requiring fault tree analysis (Figure 2.3) to arrive at an estimate of probabilities of occurrence.

Figure 2.3: Structure of mechanisms and outcomes leading to damage (Viner et al., 1995)
In the analysis of mechanisms and outcomes, the vehicle is considered a controlled system (Figure 1.1) with the driver as controller of the system, and mechanisms are either related to the controller, the vehicle system or the environment. The controller may fail as shown in Figure 2.4.

Figure 2.4: Failure in the role of a controller such as a driver (Viner et al., 1995)
The data requirement for the analyses in Figure 2.4 is still in the early stage of research. It is however possible to divide the road system into two components; a machine component, and the human component, in order to arrive at system reliability. Navin (1990), Navin and Zheng (1998) have shown that traditional engineering reliability analysis may be applied to highway geometric design. Their work could be complemented with an analysis of driver failure mechanisms. This research investigates the information processing capability of the driver with relation to the demands imposed by the road system. The premise of all information processing theories is that the human information processing capacity has a limit, and errors result when this limit is exceeded (Wickens, 1984).

Hauer (1988) has argued that the datum for the traffic safety problem is the human nature of the road user and the properties of the vehicles in use. Whilst aspects of the vehicle/road failure are founded on theory, aspects of the road user, especially road user behaviour, is still mostly treated in an *ad hoc* manner that is based on empiricism as in design consistency considerations, or on expert knowledge and experience, as is evident in road safety audit exercises. The theoretical foundation of road design has to start with the incorporation of road user behaviour into design equations. There should be more consideration of driver behaviour and characteristics other than driver eye height and perception reaction time in the equations. Driving errors go beyond the calculation of stopping sight distance, to include those due to the cognitive aspects of driving based on information processing and control functions as shown in Figure 2.4.
Inconsistent design is a violation of driver expectancy, and leads to overloading the information processing capacity of the driver. A design approach based on driver information processing theory should cover design consistency requirements as well as other aspects of driving that extend to in-vehicle information systems. Those who advocate for the use of a theoretical approach to human factors design argue that a good theory prevents the process of “re-inventing the wheel” or the search for *ad hoc* solutions (Kantowitz, 1992).
CHAPTER 3
MENTAL WORKLOAD CONCEPTS AND THEORIES

3.1 BACKGROUND

The concept of mental workload is believed to have extended from research related to physical workload, where researchers were interested in finding out the amount of work accomplished relative to energy costs (Sanders et al., 1993). Technological advancement has, however, meant that most human activity is less associated with physical work. Physical work has been delegated to machines, and human activity has become that of monitoring and manipulation of machine controls in the human-machine systems that make up humanity's world. Human activity is now characterized by perception, processing of information and decision making, which is mostly associated with mental activity. Some of the machines that human operators (e.g., pilots, air traffic controllers, etc) have to deal with have become so complex that the demands may exceed operator capability and lead to errors. Demands from complex systems may be further aggravated if human factors concerns, such as violation of operator expectancy, are not taken into account.

As systems became more complex, operators have often complained that system demands exceed their abilities (Wickens, 1992), with the implication that some authorities, like the Federal Aviation Administration of the U.S., will require certification of aircraft in terms of workload metrics. The occurrence of some accidents and near misses has also raised
questions about operator workload and system safety. The questions that need answers in these circumstances are:

1. Which functions to allocate to humans and machines based on predicted mental workload?
2. Which equipment or task designs are appropriate in terms of the workload imposed?
3. How can task difficulties be adapted to operator capabilities?

These questions have generated a great deal of research effort (reported by Moray, 1979 & Hancock et al., 1988) geared towards the development of reliable methods of assessing mental workload over the years.

Although most of the earlier research on mental workload has been done in aviation (Sanders, 1993), the concern for workload, as a human factors problem, in the road traffic system has been raised by road safety practitioners, and is the subject of various research efforts (Messer et al., 1980; de Waard, 1996, Wooldridge et al., 2000).

Basic design features of the road impose different levels of workload on the driver and, as highway features such as freeway interchanges and intersections become more complex, the limits of the driver's perception, information processing, and decision making may be exceeded. Various design deficiencies such as inconsistent design and other aspects of violation of driver expectancy often lead to increased demands on the driver. The road
design engineer should be interested to know how these affect the processing capacity of the driver.

Even more important to the study of driver workload, and its adverse effect on traffic safety, is the proliferation of road transport information systems in the road environment. Their use is intended to aid the driver in the performance of the driving task, but there are fears that they may well end up overloading the driver. On the other hand, if they take over most of the driving task, the driver may be left with so little to do that driver vigilance and alertness are reduced. The road safety community is currently looking for ways of assessing the suitability of these gadgets through an understanding of the demands they place on the driver (Green, 1999; Tsimhoni et al., 2002).

3.2 THEORIES OF MENTAL WORKLOAD

Basic to all theories dealing with mental workload is the limited information processing capacity of the operator. There are two schools of thought regarding this limitation. One theory talks about a single undifferentiated processing channel from which resources are drawn upon for task performance (Kahneman, 1973). The other is the multiple resource theory put forward by Wickens (1984) which states that different resources are available for different requirements. The main requirements in the multiple resource theory are visual and auditory resources, with a central resource pool that supports all processes. Support for the multiple resource theory comes from the time-sharing ability between auditory and visual tasks, except in cases where one of the tasks depletes the central resources. Resources are however limited whether it is the case of a single channel
processing or multiple channel processing. An operator attending to an auditory task may not have extra capacity for another auditory task.

Generally, a high demanding task will leave little or no spare capacity to attend to additional tasks and would therefore leave the operator susceptible to errors. Conversely, in a low-demand task situation, there is excess processing capacity that can be allocated to other tasks.

It is argued that resource theories cannot be separated from energetic theories (Hockey, 1997). Resources are not only limited but effort is required to mobilise resources; and the amount of effort required for a particular task has a direct bearing on operator workload (Mulder, 1980). According to Hockey (1997), a central compensatory control mechanism is said to compare the present cognitive state of the operator with the required state and any deficiency is compensated for by the recruitment of further resources. The recruitment of additional resources is done at the expense of subjective effort and at a cost. There are two ways in which this mechanism can be activated: (1) as a result of increased demand, and (2) as a result of diminished operator state. The effort required in the former is task-related effort, and the latter is state related effort. In the case of task-related effort the operator needs to maintain performance even though task demands are increasing. The operator can be in a diminished state as a result of monotonous tasks, fatigue or under the influence of drugs. In this case, the control mechanism acts to compensate for the diminished state of the operator, and it is therefore state-related effort. Strategy may also be employed in order to deal with the increase in external task
demands and the least of such strategy can be inaction. Whilst this last option has no
costs on the operator and no effort requirement as a result, performance decreases
considerably.

3.2.1 Defining of Mental Workload

A precise definition of mental workload has been a problem for researchers for sometime
(Jex, 1988; Reid & Nygren, 1988). Workload is a multifaceted phenomenon and it is easy
to concentrate on one aspect whilst other aspects are very active. To define mental
workload de Waard (1996) made a distinction between external demands of a task and
the effects of these external demands on the operator. The fact that one operator may be
more endowed than another is well accepted and may affect the ease or difficulty which
external demands may have on the operator. In addition to the consideration of individual
capabilities, the effect of an external task demand on an operator is also determined by
the performance goals set by the operator, motivation, strategies, and operator state.
‘Mental Workload’ or the ‘Experienced Mental Workload’ is therefore the proportion of
the operator’s processing capacity that is used in the performance of a task (O’Donnell et
al., 1986).

Jex (1988) defines Mental Workload as the operator’s evaluation of the attentional load
margin (between their motivated capacity and current task demands) while achieving
adequate task performance in a mission-related context. According to Figure 3.1 the
operator’s capacity, physiological or motivated is not constant all the time. It may
decrease due to fatigue or boredom, and may increase due to practice.
The relevance of Jex's (1988) definition is that performance goals may no longer be purely the prerogative of the operator. In certain tasks which affect the welfare of society (e.g., pilots, air traffic controllers, drivers, workers in nuclear power plants), society expects certain minimum performance levels from operators and this should determine the task demands. Task difficulty would now be purely dependent on the operator state, strategy, and capacity.

Some tasks are over-learned and require little or no effort from the operator. These tasks are performed at the automatic level, and involve no conscious information processing, as opposed to deliberate level processing, which is conscious and requires the use of working memory (Reason, 1990). Conscious information processing takes time, and time or the speed with which information is processed has been suggested as an indication of, or a measure of workload (Mulder, 1980; de Waard, 1996). If however the time available

Figure 3.1 Concept of Workload Margin
to perform a task is limited, then time also becomes a factor for the workload experienced by the operator. As it is, human activity happens to be regulated by time and tasks often have time constraints. Hence ‘Mental Workload’ has also been defined as the time rate at which an operator is required to carry out a certain task (Messer, 1980).

3.2.2 Assessment of Mental Workload

The human factors designer is concerned about the level of workload that system design would impose on the operator, and would take steps to regulate workload so that it does not exceed operator capabilities. However, in order to regulate workload to the advantage of the operator, the designer should be able to assess the workload that system design would impose on the operator, as well as assess operator capabilities. Hancock & Caird (1993) argue that although a clear recognition of the importance of the prediction of workload exists, there are relatively few theoretically grounded models with which to attack the problem. This concern is also echoed by Hendy et al. (1996), who blames the trend on the multi-faceted nature of the workload construct. Any model developed to predict workload should consider all the factors that come into effect for the operator to experience workload.

Workload may be dependent on the psychological/physiological state of the operator, but from the above definitions, it is easy to see that other key determinants are external task demand and the time constraints of the task. From a survey of the literature (Jex, 1988; Reid & Nygren, 1988; Liao & Milgram, 1993); Hendy et al. (1996) argued that since external load intensity and time constraint have proved to be successful determinants of
workload, they should each capture some aspects of operator workload and that, a way should be found to combine them. They added that any model which combines these aspects will have a higher predictive power compared to those that consider one aspect almost to the exclusion of the other.

The workload which the operator experiences at the end of the day is also a function of the strategies adopted. As stated elsewhere, operators may change from knowledge-based to rule-based to skill-based processing in order to adjust the workload actually experienced, or they may abandon the task completely and have zero workload. According to Parasuraman & Hancock (2001), workload may be driven by the task load imposed on the operator from environmental sources (e.g., load intensity, time constraint, etc), but it is also mediated by individual response to the load with their skills, and task management strategies. Operator performance should be a joint consequence of the effects of task drivers and the mediating strategies of the operator known as adaptation (see Figure 3.2).

![Image](image.png)

Figure 3.2: Inter-relationships between workload drivers, workload, and performance (Parasuraman, 1997).
Various studies have failed to show an association between workload determinants and experienced workload (Sperandio, 1971; de Waard, 1996). Sperandio (1971) observed that air traffic controllers handled a large number of aircraft which according to the rule of association should have given high workloads. The controllers achieved this by decreasing the amount of time they spent on processing each aircraft. Air traffic controllers may also pass some of their workload to other controllers thereby reducing their workloads. In experiments to measure driver workload, de Waard (1996) also experienced dissociation between workload determinants (notably road complexity) and measured driver workload. The explanation was that drivers used their speed management strategies to reduce the workload they experienced. If indeed operators used adaptive strategies to mediate task demands from external sources, then workload assessment strategies should also include these strategies in workload models. In this light, Kantowitz (cited by Kantowitz and Simsek, 2001) defined workload as “an intervening variable similar to attention, which modulates the tuning between the demands of the environment and the capabilities of the organism”.

3.3 MEASUREMENT OF MENTAL WORKLOAD

The importance of workload to an individual’s daily activities means that we need to assess it. Assessment involves identifying the determinants and how they interact to effect workload, as well as looking for appropriate techniques of measuring it. The same reasons put forward for defining and assessing workload also apply to the reasons why it should be measured accurately. A couple of measures are in use, and it is not unusual for
researchers to use two or more measures in order to capture workload since most of the measures can be inappropriate in some circumstances.

3.3.1 Characteristics of measures

Workload measures should have certain characteristics to make them suitable. These include sensitivity, selectivity, interference, acceptability, and reliability (Jex, 1988). These characteristics are explained in the following passages:

1. Sensitivity: the measure should show a monotonic trend with respect to mental workload i.e., it should show changes in mental workload.

2. Selectivity: the measure should not be affected by things not considered to be part of mental workload. A measure which is affected by physical workload as well as mental workload can be said to be lacking in selectivity.

3. Interference: the measure should not interfere with, contaminate, or disrupt performance of the primary task whose workload is being measured. This is a major aspect of secondary task measures which measure performance on the main task by introducing a secondary task.

4. Acceptability: the technique should be acceptable to the operator whose performance is being measured. The technique should be easy to learn, administer, and it should be easy to be used in the field as well as in the laboratory. It should also not require very high costs.

5. Reliability: the measure should have proven test-retest repeatability both across time and across subjects with comparable practice on task.
3.3.2 Workload Measures

It is difficult for any one measure to have all the above characteristics. Measurement techniques that have been used can be classified into the following broad categories: performance measures, physiological measures, and subjective measures (O'Donnell & Eggemeier, 1986).

1. Performance measures: these comprise primary task performance measures and secondary task performance measures.
   a. Primary task performance measures would seem the most appropriate measure of workload on a task since high performance would indicate low workload and vice versa. It is however possible for two tasks of different task demands to show the same performance result as long as capacity is not exceeded. Wickens' (1992) suggestion for solving this problem is to keep on increasing the task demand for the task whose workload is to be determined until performance degradation sets in. The additional increase in task demand before this happens should give a measure of the workload.
   
   b. Secondary task performance measures developed with the logic of spare capacity that is not being utilized by the main task. The more the primary task demands from the operator, the less resources available for secondary task performance. In this case the operator is instructed to concentrate on primary task performance, and use spare capacity on secondary task
performance. The instructions can be reversed and the operator asked to concentrate on the secondary task, so that decrements in primary task performance would indicate the difficulty of the primary task. The success of secondary task measures would depend on the extent to which the two tasks are using the same resources. If, as indicated in multiple-resource theory (Wickens, 1984), the two tasks are using different resources, then a secondary task measure would be inappropriate. The dilemma with this requirement however is that interference increases when the two tasks are sharing the same resources. Some examples of secondary tasks that have been used include choice reaction time (reported by Park, 1987), random digit repetition (Macdonald et al., 1975), delayed digit recall (Zeitlin, 1993), and mental arithmetic and memory search tasks (Cnossen et al., 2000).

2. Physiological measures are related to the body’s reaction to task demands. It is assumed that information processing involves Central Nervous System activity and this activity can be measured. The most frequently used measure in this category to register workload is the electrocardiogram (ECG) (Brookkhuis & de Waard., 2001), and prime measures include the time between R-waves, Interbeat-interval (IBI) and the heart rate variability (HRV).

Eye fixation is another measure that is widely used with some confusion as to whether it should belong to the performance measures category (de Waard, 1996).
For tasks that are highly visual in nature (e.g., driving), another visual task could be used as a secondary task. Various studies (Wilson & Eggemeier, 1991; O’Donnell and Eggemeier, 1986) have shown a direct relationship between the difficulty of a task and high fixation time. Perhaps one of the most widely used areas of the eye fixation measure is in driver workload research. Green & Tsimhoni (2001) have catalogued the origin of driver visual demand measure and its popularity as a workload measure. Drivers receive more than 90% of driving task information visually (Alexander et al., 1985). So, by measuring driver visual demand with visual occlusion techniques, the driver’s information needs on the road can be measured.

3. Subjective workload measures are the operator’s own judgment about the extent to which the task is affecting them. Many investigators (Wickens, 1984: Sanders et al., 1993, de Waard, 1996) agree with Sheridan (1980) that subjective measures come closest to tapping the essence of the mental workload concept, with de Waard (1996) adding that “no one is able to provide a more accurate judgment with respect to experienced mental load than the person concerned”. To make this technique appear easy, operators are presented with a scale on which they fill in the extent of task difficulty. The scale normally ranges from very easy to impossible. The scale can be unidimensional, like the Cooper-Harper scale (Sanders et al., 1993), or multidimensional in which case mental workload is treated like a multidimensional construct and the operator has to indicate task difficulty in at least three dimensions. These three dimensions include: task load,
time pressure, and psychological stress. The most frequently used multidimensional scales are the Subjective Workload Assessment Technique, SWAT (Reid & Nygren, 1988), and the NASA Task Load Index, TLX (Hart & Staveland, 1988).

3.4 MODELS OF MENTAL WORKLOAD

The need to predict mental workload and its effects on operator performance has resulted in the development of several models which attempt to explain the interrelationship between task load, mental workload and operator performance. Some models may dwell on certain aspects of mental workload, but fundamental to most models is the limited information processing capacity of the human operator. This is true either in the case of single or multiple processing channels (Wickens, 1984).

With a limitation of processing resources, the operator’s information processing channel is overloaded and mistakes are made. Also, too little information or low task demands (otherwise known as work under-load) make the operator’s task very boring. The operator becomes inattentive and fatigued making him/her susceptible to errors. It is believed that somewhere in between the extreme states of information overload and under load, there is an optimum level of processing demand at which errors are minimized. This is in consonant with the Yerkes-Dodson Law (1908) that has been used to explain the relationship between workload, performance and arousal (demand). Figure 3.3 is a diagrammatic representation of the Yerkes-Dodson Law. The origin of the law is from an experiment which the authors conducted in order to determine the discriminating ability
of mice for various levels of electrical shock. The results of the experiment showed the mice performing badly at both low and high levels of electrical shock. They however performed well at moderate levels of shock. Over the years the law shifted to human beings with the denominator changing from electrical shock to arousal, task complexity, demand and workload (Teigen, 1994) and it popularly came to be known as the Inverted U-shaped Law.

![Yerkes-Dodson Law](image)

Figure 3.3: Yerkes-Dodson Law

Meister’s (1976) proposed a model which deals mostly with the overload side of the operator. Meister’s model has three regions; region A is the region of low workload and high performance as a result; region B signifies declining performance with increased task demands; region C is the region of least performance as a result of high task demands and hence catastrophic high workload.
Since performance has been found to remain constant over a range of task demands, and high workloads may result from deactivation caused by low demand/boring tasks, de Waard (1996) combined Yerkes-Dodson law (1908) with the Meister model (1976) to give Figure 3.4 above. At moderate levels of task demand, performance is high and it is kept at a reasonably constant level as task demand increases as a result of operator effort (task-related effort) to match increased task demand with additional processing resources. Operator effort is however at the expense of increased workload which is also represented in Figure 3.4. When all the available resources have been utilized (at operator capacity), additional increase in task demand is accompanied by decreased performance. The D-region added by de Waard to Figure 3.4 represents the situation when operator state is affected. This may be as a result of prolonged low task demand situations which
deactivate the operator or the operator may be under the influence of drugs/alcohol. In which case the operator has to make effort to maintain performance in his/her poor state, hence the effort expended in this region is termed as stated-related effort.

**Time Constraint Models**

The effect of time on information processing is accepted by many (Reid & Nygren, 1988; Hendy et al., 1997; Hancock & Chignel, 1988), but exactly how this effect comes about is sometimes a controversial issue. Zakay (1993) attributed time effect of information processing to be as a result of resource sharing between time estimation and the task at hand. His explanation was that when an operator is given an indication of limited time availability, the operator's attention becomes divided between the task at hand and questions like “what time is it?”, “how much time have I got left”, “will I finish in time?”. Whilst this may be true in the case when the operator is given time to do a task, experiments on choice reaction time have also shown that reaction time increases with the number of alternatives (task complexity) (Park, 1987). This further supports the notion that conscious information processing takes time (Mulder, 1980; de Waard, 1996); an indication that the time available to do a task will affect operator workload.

In a study of the literature to find a universal definition of mental workload, Reid & Nygren (1988) found that most researchers found time pressure to be one of the key determinants of workload. Among the various techniques for measuring mental workload, subjective workload metrics appear to show the highest consideration of time constraint in the assessment of workload (SWAT, Reid & Nygren, 1988; TLX, Hart &
Staveland, 1988). It is also interesting to note that even though the effect of time is acknowledged in the workload literature, very few models have included time pressure as a determining factor. Two of the models dealing with time pressure are considered;

**Hancock & Chignel (1988) Model:** In this model, mental workload is described in a three-dimensional representation comprising: (a) the distance from the perceived goal (complexity), (b) the effective time for action, and (c) the level of operator effort. For a particular level of operator effort, Figure 3.5 shows the effects that perceived distance from the goal and effective time for action have on operator workload.

![Figure 3.5: Mental Workload expressed as a function of perceived distance from goal state and effective time for action (Hancock & Chignel, 1988).](image)

Perceived distance from goal is the operator's comparison between his/her state and what is required from the task. For the distance of \( D_0 \) to \( D_F \), the effect of perceived distance is
negligible. Distance has effect from $D_F$ to $D_C$. Beyond $D_C$, the effect is so strong that performance may degrade in a catastrophic manner. The limit of $D_C$ for each operator has something to do with training and experience. On the time scale, $T_M$ is the point where the operator has so much time that the task could be meaningless. As time for action reduces, a point $T_C$ is reached when the effect of time on workload starts to be noticeable. Further reduction of effective time for action results into increases in workload until time $T_F$, below which the operator cannot reconcile the task requirements. The shaded area indicates a region of inadmissible workload as a result of a combination of adverse values of time and goal distance.

Within the admissible limits of distance and time in Figure 3.5 are isodynamic workload contours resulting from increasing workload $W_{lD}$ on the distance axes, $W_{lT}$ on the time axes, and the $W_{lC}$, the combined effect of distance and time.

**Hendy et al. Model (1997):** Like most of the workload models, this one is also based on the human information processing theory and the idea of the human as a limited-capacity processor. The error and performance prediction aspect follows that of Figure 3.4 and it represents the overload part of Figure 3.4, which is derived from the Meister (1976) model. In addition, the model defines the demand function explicitly in terms of load intensity and time load, arguing that every human problem solving is subject to some form of time constraint, either explicitly or implicitly. Figure 3.6 shows how the various components associate to cause workload.
The psycho/physiological state of the operator affects the capacity through the effort that can be exerted. With time pressure, effort is exerted to make more processing resources available. This increases the apparent capacity, thereby making more time available for the task (hence reducing task difficulty). The amount of resources however has an upper bound at capacity. Assuming that a certain task can be equated to $B_r$ bits of information and since the effective rate of processing information is at operator capacity $C$ bits/sec, the decision time $T_r$ required to process this information is given by

$$T_r = \frac{B_r \text{ bits}}{C \text{ bits/sec}} \quad \text{(3.1)}$$

Suppose the time available to perform this task is $T_a$, then the information processing load or time pressure (TP) will be given by
TP can alternatively be expressed in terms of relative demand for processing resources. The rate of information processing demand (RID) can be expressed as the ratio of the total information and the time available to process it.

\[
\text{RID} = \frac{B_t}{T_a} \quad \text{(3.3)}
\]

\[
\text{TP} = \frac{T_r}{T_a} = \left( \frac{1}{C} \right) \frac{B_t}{T_a} = \frac{\text{RID}}{C} \quad \text{(3.4)}
\]

This expression of TP follows the definition of workload as the proportion of the operator's information processing capacity that is utilized to perform a task. Channel overload occurs when TP>1. When TP>1, the human information processor adapts through effort investment to match demand with capacity.

The proposed relationship amongst the various components of the model is given in Figure 3.7. The top part of the figure represents the relationship between rate of information demanded (RID) and rate of information processed. As the demand increases, effort is exerted so that the rate of information processed (RIP) matches the rate of demand, until the ceiling for information processing is reached at capacity. The ideal channel would be the one for which the rate of information processing (RIP)
matches rate of information demanded (RID) all the way. Channel capacity can however
vary depending on the state of the operator; through fatigue, motivation, anxiety, etc.

Figure 3.7: Hypothesized relationships for the time-constrained behaviour of the human
information processor (HIP) in terms of rate of information demanded, rate of
information processed, performance, and error. (Hendy et al., 1997).

Performance is defined as the ratio of information processed (RIP) to the information
demanded (RID). This is shown in the bottom half of Figure 3.7, together with that for
errors. For the time when processing rate matches demand rate, performance is constant. The number of errors increases as the quantum of unprocessed information accumulates.

3.5 CONCLUSIONS

This chapter looked at the concepts of operator workload, and in particular, the techniques used in its assessment. The assessment and prediction of mental workload for design purposes requires that the various components that affect workload be considered in the assessment process. When considering the issue of mental workload it is sometimes easy to focus on the physical aspects of the task. A survey of the literature and the theory however indicates that, in addition to the physical task load, other parameters are in operation when the operator experiences work. These are as follows:

1. the operator’s psycho/physiological state,
2. the physical demands of the task
3. the strategies adopted by the operator, and
4. the time available to do the task.

Workload cannot therefore be assessed without the consideration of the above determinants.
CHAPTER 4
DRIVER WORKLOAD CONCEPTS AND ASSESSMENT

4.1 BACKGROUND

The importance of human factors in the design and operation of the highway system has already been discussed in earlier chapters. Of direct relevance to human factors is the phenomenon of design inconsistency, which is brought about as a result of the design speed concept. Inconsistent design in turn has a direct impact on the violation of driver expectancy, which subsequently leads to high driver workloads. Violation of driver expectancy means that more time is required to process driving information, and in the situation where information sources are competing for the limited processing capacity of the driver, driving errors are possible.

Also, the driving scene is often complex; comprising of changing road situations, different drivers and other road users, weather patterns, in a constantly changing environment. The complexity of the road system is ever increasing with more vehicles on the road, and sophisticated design associated with freeway interchanges and other road features.

In addition to the above, the road system has seen a proliferation in the use of information systems both inside and outside the vehicle. Whilst these systems are designed to aid the driving task, there is concern that they may in fact overload the driver. This concern has seen the development of several guidelines, which, according to Tsimhoni et al. (2002),
are lacking in their consideration of the full implications of the effects of workload caused by the various systems. Whilst most of the concern is with regards to overloading the driver, there is also a concern that devices, which are geared towards automation, might leave the driver with so little to do that driver deactivation results. To understand driver workload and how additional tasks might affect it requires a closer look at the driving task.

4.2 THE DRIVING TASK

The task of the driver can be categorized at three hierarchical levels with increasing complexity: (a) vehicle control; (b) vehicle guidance; and (c) route navigation (Alexander et al., 1985). Control level tasks involve the driver's interaction with the car in terms of speed and position control through the accelerator, the brake, and the steering wheel. Operations at this level are highly over-learned, mostly involving automatic processing with little of the driver's information processing capacity involved. Guidance level tasks are next in the hierarchy in terms of complexity. This level involves conscious processing, with the driver continuously evaluating the position of the vehicle with respect to hazards on the road, and making decisions about the speed and direction of the vehicle, which are translated into control actions. The information needs at this level are acquired from the road (e.g., geometry, hazards), the traffic (e.g., density, speed), and traffic control devices. At the navigation level, decisions regarding trip plans, choice of route and mode of travel are made. This level is the highest in the complexity hierarchy.

For safe and efficient operation of the road system, the driver is continuously seeking information at all three levels of the driving task. At any one time, the driver is involved
with performance at one, two or all three hierarchical levels of the driving task, which sometimes results in competition among information needs. When this happens, primacy of information needs becomes very important. This refers to the relative importance of the various levels of operation of the driving task. The consequences of errors at the control and guidance level are the highest when compared to errors at the navigation level. The more complex the situation, the more information is needed to resolve the uncertainty associated with the complexity. With the complex environment in which drivers often find themselves, it is required that they stay alert and make proper judgments and decisions in the control of the vehicle to the extent that driver information processing capacity is sometimes exceeded and driving errors become likely.

At the heart of all information processing and workload theories is the limited information processing capacity of the operator. However, the use of capacity in the determination of workload is vague. Perhaps the measures that come closer to capacity considerations are secondary task measures which measure workload in terms of the available spare processing capacity. Other workload measures compare situational effects with a baseline case (de Waard, 1996) and therefore have no way of estimating when the operator might reach capacity. The best way to include capacity might be through the concept of reaction time. According to Figure 2.2 (refer Chapter 2), high information content is associated with high reaction times, that is, the time required by the driver to process the information and arrive at a control decision increases. The linear relationship between reaction time and information content seems to suggest a constant rate of information processing. Any rate of processing above this rate would therefore indicate
an overload of the operator's information processing capacity. This follows the Messer (1980) definition of driver workload: "the time rate at which the drivers must perform a given amount of work or driving task". The use of reaction time in driving has however been limited to driving dynamic safety design. In complex situations, longer reaction times can also mean that different information needs may be competing for the limited information processing capacity of the operator.

4.2.1 Road Design and Driver Workload

The dependence of driver workload on certain aspects of road design is well acknowledged. Perhaps owing to accident experience and the fact that it is easily measured, radius of curvature has often been used to investigate driver workload (McDonald et al., 1975; Wooldridge et al., 2000; Green & Tsimhoni, 2001). Van der Horst & Godthelp (1989) reported on the effect of lane width on the driver's visual demand, which is also generally regarded as a measure of driver workload. Whilst most of the above have been based on experiments, expert opinion also associates driver workload with various design features of the road. According to Messer (1980), 21 highway safety experts gave subjective workload ratings to nine (9) basic highway geometric features (e.g., tangent, bridges, horizontal and vertical curves, intersections, and lane width). The ratings ranged from 0, meaning no problem, to 6 meaning critical problem. These ratings were used in an equation developed to estimate the workload at a feature depending on the frequency of the feature, sight distance, and whether or not the driver is familiar with the road.
The workload due to a road feature also depends on the location of the feature with respect to other features, especially tangents. When complex road features such as sharp curves follow long tangents, inconsistent design results. Inconsistent design leads to the violation of driver expectancy, which in turn causes high driver workloads. Expectancy violations are related to higher reaction times, which have been reported to be 35% in excess of those required under normal circumstances (Johannsen et al., 1971). This means that although the driver can process information at a certain maximum rate (capacity) under normal circumstances, resources are not fully mobilized to deal with the sudden surge of processing needs. The driver/operator requires time to mobilize or divert extra resources to the present task. Expectancy violations would normally occur at such high speeds that there is not enough time to process the information presented to the driver.

Because of its impact on road safety, design consistency has been a subject of many studies, leading to the development of safety design criteria with regards to harmonizing operating speeds and design speeds, and harmonizing operating speeds between adjacent road design elements (Lamm et al., 1999). However, the subject of design consistency is often addressed without any reference to its human factors implications or any reference to driver workload. Inconsistent design may lead to driving dynamic failure as a result of inappropriate speed choices, but at the same time, it also impacts on the cognitive aspects of driving through the violation of driver expectancy and the information processing load associated with this violation.
4.2.2 In-Vehicle Information Systems and Driver Workload

Over the years the road transport industry has seen a huge increase in the use of in-vehicle information systems such as adaptive cruise control systems, rear-end collision avoidance systems, obstacle/pedestrian detection systems, navigation/routing systems, real-time traffic and traveler systems, etc., and the trend is expected to continue (Tsimhoni et al., 2002). It is even speculated that future profit margins with respect to the sale of these devices will outweigh that derived from the sale of vehicles (Tsimhoni et al., 2002). With this increase in the use of these devices, there is a growing concern over the safety of the driver that has lead to research and the setting up of guidelines for the manufacture and use of in-vehicle information systems (UMTRI, 2003). The concern is that these devices will overload the information processing capacity of the driver, or cause distraction of the driver with severe safety consequences. With approximately 5 million vehicles equipped with in-vehicle navigation systems, Japanese police records showed at least 59 crashes between August 1997 and May 1998 associated with the use of navigation systems (Green, 1999). Whilst there may not be enough statistical evidence to associate crashes with the use of these devices in North America and Europe (mainly as a result of low usage), it was estimated that at the present pace, US roads will record 21 deaths and 2100 injuries in the year 2007 due to the use of navigation systems (Green, 1999). These estimates are based on the visual demand (workload) that the devices will impose on the drivers; since time spent collecting information from in-vehicle devices will be time spent with eyes off the road (the main task of driving). The effect on older drivers is even more profound since these drivers tend to exhibit lower processing abilities compared to younger drivers (Tsimhoni et al., 2002).
With all these devices installed in the vehicle, it is possible that at any one time, a couple of them may demand the attention of the driver. A driver could be traversing an intersection or a difficult curve when information about the weather or the traffic ahead becomes available and is presented to the driver. To prevent the workload that this influx of information might bring, a central monitoring/coordinating interface, which regulates the quantum and timing of information to be presented to the driver has been a subject of research projects like the GIDS (Generic Intelligent Driver Support) project (Michon, 1993), and ARIADNE (Application of a Real-Time Intelligent Aid for Driving and Navigation Enhancement). Such an interface must be able to estimate the demand from the road as well as the demand from each of the devices in order to schedule properly. The interface must also be able to estimate the limits of information processing within which the driver can operate if the scheduled information is not to overload the driver.

4.3 ASSESSMENT OF DRIVER WORKLOAD

Analysis of the driver workload problem clearly indicates that it requires a two dimensional approach; one dealing with off-line design and the other dealing with on-line design. For off-line design, the designer is concerned with the way road design features affect the safety performance of the driver as a result of the workload induced by the configuration of road design features. On-line design deals with the scheduling of in-vehicle information systems so that the driver is not overloaded with the extra information. This requires knowledge regarding the extent to which the driver is already burdened by the task of driving as well as the information processing limits of the driver.
To achieve both designs requires a proper knowledge of driver workload, its theory and measurement, the development of a predictive model that can give absolute measures of driver workload, and performance levels at various locations on a road segment. Accordingly, this has been a difficult task in many workload applications as a result of the multifaceted nature of the workload concept. Because of the multi-faceted nature of workload, the likelihood of concentrating on certain aspects whilst ignoring other important aspects cannot be ruled out. It is believed that a model of a higher predictive power can be developed by combining all the aspects of workload in a theory that supports the workload concept (Hancock and Caird, 1993; Hendy et al., 1997). Generally, the principal dimensions of workload are load intensity, time constraint and psycho/physiological aspects, and they should be considered in any model of operator workload (Hendy et al., 1997; Reid et al., 1988; Jex, 1988; Wickens, 1989). Their combined effect to produce workload is finally dependent on the intervening strategies of the operator, so that the final workload experienced by the operator is determined by the strategy adopted by the operator. The proper assessment of driver workload should also start from an investigation of the various components that contribute to it, as well as strategies employed by the driver to manage workload.

4.3.1 Determinants of Driver Workload

What is apparent from most experiments conducted to study driver workload is that driver workload depends on load intensity as presented by the road layout (design) or in-vehicle devices. Various experiments have studied the effect of radius of curvature, lane width, or the layout of the road on driver workload (de Waard, 1996; McDonald et al.,
1975; Wooldridge et al., 2000; others cited by Green & Tsimhoni, 2001) and the consensus is that as road complexity increases, driver workload also increases.

Another contributing factor to driver workload that has been recognized by researchers but not often used in the determination of driver workload is the operating speed the driver adopts. Senders et al. (1967), (later confirmed by McDonald et al. (1975)) have shown that as the operating speed increases, the attention demand of the road also increases. Van der Horst & Godthelp (1989) reported an experiment in which subjects drove on a tangent section at different speeds with voluntary visual occlusion (a measure of visual demand). The results showed that as speed increased, drivers' visual occlusion time decreased. In other words, drivers paid more attention to the road showing a higher visual demand from the road. Cnossen et al. (2000) made subjects drive a simulator at a slow speed (accurate), a fast speed, and when following a lead car, with or without a memory task. The effect of the speed scenarios and the memory task on driver workload was estimated using different workload measures (performance, subjective, and physiological measures). Each of the measures showed results comparable to Figure 4.1 with workload increasing with driving speed.
Despite the evidence about the relationship between driver workload and operating speed, some (de Waard, 1996; Wooldridge et al. 2000) measures and applications of driver workload have used complexity of the roadway as the only determinant of workload. Where driving speed is considered, it is mostly kept constant in field or simulated driving tests (Wooldridge et al. 2000). A method for evaluating driver workload presented by Messer (1980) is based on subjective ratings of various road features for a driver at 93km/hr. These ratings are further modified depending on the site distance to the feature, the familiarity of the driver with the road, and driver expectation. Whilst the subjective ratings account for the complexity of the road feature, the modification factors account for the speed at which the driver will traverse the feature. Limited sight distance, driver unfamiliarity and violation of driver expectancy mean that the driver will approach the feature at an inappropriate speed. In experiments to determine appropriate measures of driver workload, de Waard (1996) observed decreased workloads in complex road situations, and blamed it on the ability of the driver to adjust speed in order to keep
overall workload within capacity. This makes it very difficult to determine absolute measures of driver workload without speed considerations.

The general workload literature has identified psycho/physiological factors, load intensity and time constraint as the main determinants of operator workload (Hendy et al., 1997). In the case of driver workload, the time constraint aspect is induced with the operating speed. The information utilized by the driver to make driving decisions may be concentrated at one spot (as for a narrow bridge or a lone intersection), but road information sources are mostly distributed on a per kilometre basis and are therefore expressed as such. For example, curvature is measured in degrees per kilometre and we can measure intersection density as number of intersections per kilometre. Hilliness and bendiness are measured on a per kilometre basis as well as is the roughness of the road surface.

The information due to these various complexities of the road can therefore be normalized in one unit as bits of information per kilometre. Therefore, if a road segment has for instance, $H$ bits of information per kilometre and two drivers traverse this road segment at 50km/hr and 80km/hr respectively, it is obvious that the time available to the slower driver to process the information imbedded in one kilometre is more, and will therefore involve less time pressure. The first step towards the development of any predictive model of driver workload should be the incorporation of at least time constraint (speed) and road complexity.
Measures of driver workload using road complexity as the only determinant can show an increase in workload with increased road complexity under controlled conditions (of speed) as shown in the Wooldridge et al. (2000) experiments. Researchers who use this technique do so with recognition of the effect of speed and the speeds at which the experiments are conducted are often stated. Failing to control speed may sometimes result in the data not showing any association between increased road complexity and measured workload as reported by de Waard (1996). This seems to suggest that speed does not only contribute to driver workload; it may also be acting as an effective tool that the driver uses to control experienced workload. If this controlling ability of the driver is not considered in workload assessment, then association cannot be established. The controlling ability is known as adaptation in the workload literature and its influence in driver workload assessment is more direct, making driving to be termed as a self-paced task.

From the above assessment, driver workload may be driven by the following factors:

a. driver state: affected by fatigue, drugs (including alcohol), age, experience

b. road environmental factors: including road layout (design), surface conditions, traffic, etc.

c. in-vehicle information systems, and

d. adaptive strategies: including speed and its management.

It may not be easy to quantify the effects of all of the above; especially driver state factors in a model, which may result in some aspects of generalization. However, a large
proportion of road factors, speed and its adaptive control are quantifiable to some extent and should be considered in any model of driver workload.

4.4 ADAPTATIVE CONTROL IN DRIVING

Mental workload may be related to external task demands and operator abilities, but it is also mediated by the operator in order to counteract the stressful effects of tasks. Mediation can be by way of mobilizing additional resources to match task demands, or choosing processing structures which place fewer demands on the operator’s processing capabilities; to direct physical intervention of the operator as explained elsewhere in this report with regards to task reducing strategies of air traffic controllers. This mediating capability of humans in human-machine systems has generally been termed “adaptation” (Parasuraman et al., 2001; Hendy et al., 1997; Summala, 1997).

Driving has long been considered a self-paced task (Naatanen & Summala, 1974, 1976, and Wilde, 1982), making it one of those areas of human activity where there is a high possibility for adaptation. It starts from planning the journey right up to arrival at the destination. To some extent, the driver can choose the time of day the journey can be made in order to avoid being in heavy traffic and can make a choice among available routes in order to make the journey easier. In addition, the choice of mode of transports is also available, all adding together to determine how convenient the journey can be.

The adaptive capabilities available to the driver have been explained in many theories ranging from car-following models (May, 1990), to the risk models of Naatanen &
Summala (1974, 1976), and Wilde (1982). The driver generally reacts to situations on the road, whether due to traffic or road layout, by adjusting behaviour either in terms of speed or evasive action. Some of the models describing driver behaviour in the traffic are discussed.

Driver reaction to situations on the road as a way of explaining safety problems was first mentioned by Gibson & Crooks (1938, cited by Summala, 1997) in the late 1930s, and again by Smeed (1949, also cited by Summala, 1997) in the late 1940s, but it was not seriously investigated until the risk models in the 1970s. Before these models, mishaps on the road were blamed on the accident-prone driver. It was believed that there were some clumsy drivers in the traffic system, and that roads can be made safer by weeding out these drivers. The accident-prone driver theory was questioned by Forbes (1972), who from analysis of existing accident data, concluded that most accidents are caused by one-time offenders whose capabilities are sometimes overtaxed by the driving task. The risk models came with the realization that driving is a self-paced task and that while the driving situation can sometimes overtax the capabilities of the driver, the extent can be regulated by the driver through speed management.

Wilde’s (1982) theory of risk homeostasis posits that the total risk on the road will always remain the same, irrespective of safety interventions, because driver behaviour is acting to keep subjective risk at a constant/target level (see Figure 4.1). The fact that drivers are seen to take risky actions in the presence of improved safety was evidence to support this theory. For example, a driver whose vehicle is fitted with studded tires will
tend to drive faster. This theory is not without opponents, and vigorous analysis of data by Evans (1991) has shown mixed results. The fact that there exists a vast difference between accidents on interstate roads and rural roads was one of Evans’ simple arguments. Furthermore, the fact that there has been a steady reduction in accident rates in industrialized countries seems to suggest that safety interventions over the years are paying off. It is argued that for the risk homeostasis theory to hold, the driver has to be aware of the target risk level; there is no mechanism to suggest this.

Figure 4.2: Wilde’s Risk Homeostasis Model (Wilde, 1982)

Naatanen & Summala (1974, 1976) approached the risk theory with a slight variation from that of Wilde (1982). They proposed that the driver sets a target speed for motivational reasons which may include the desire to save time or to impress peers, and while this speed can vary from one section of the road to another, it is set so that it does not exceed the perceived maximum safe speed. This way, the driver maintains a zero-risk level as the road is traversed; hence the name zero-risk theory. Evans argues (1991) that since the maximum subjective speed is chosen depending on the road condition, it is
bound to increase each time there is an improvement on the road, or depending on the success in the last run. Compared to the variability in the objective maximum speed (because of variations in frictional factors), the possibility of a mishap cannot be ruled out.

Drivers will speed because speed serves the motive of getting to the destination in a shorter time. They do however adjust their speeds when faced with difficult situations on the road to the extent that the estimated risk (subjective risk) is zero.

With the failure of the risk models to give an undisputable explanation of driver speed behaviour, the only other plausible explanation is that drivers (like all human operators in man-machine systems) do intervene to reduce the effects of system tasks, and they do so by varying their speed. Speed has already been identified as a major determinant of driver workload, and since driving speed is normally under the control of the driver, it comes in very handy in the management of workload. Unlike risk models, which require drivers to have an estimate of some target risk, or the maximum objective safe speed, drivers should know their own processing limits and should be able to adjust speed so that this processing limit is not exceeded. The same argument was put forward in support of the use of subjective measures of workload. The operator is the person directly feeling the pressures of the task, and if they say that a particular working situation is giving high workload, the situation should be adjusted to reduce the workload (de Waard, 1996).
Figure 4.3: Zero-Risk Model (Naatanen & Summala, 1974)

Pioneering research relating to driver speed behaviour with respect to driving task demands were conducted by Senders and his colleagues in the late 1960s (Senders et al., 1967). They conducted a couple of experiments on the visual demands of the road in which they occluded the vision of drivers for various durations and allowed them intermittent but constant glimpses of the road at the end of each occlusion time. In one of those experiments, they showed that the drivers reduced their speeds when occlusion time increased (Figure 4.4). The longer the occlusion time, the more the information required
to resolve the uncertainty about the road ahead. From these experiments, Senders et al. (1967) concluded thus,

"..drivers tend to drive to a limit. We suggest that the limit is determined by when the driver's information processing capacity, either real or imagined, is matched by the information generation of the road, either real or imagined". (Senders et al., 1967, 17)

It is obvious that the driver's information processing capacity cannot be termed as something "imagined" since it is an intrinsic part of the driver, nor can the information generated by the road be imagined.

![Graph](image)

Figure 4.4: Relationship between occlusion time and terminal speed (Senders et al., 1967)

One does not need to look far to show that drivers reduce their speeds with increased task demands. Speed-density models in traffic flow theory are very good examples of driver speed behaviour with respect to driving task difficulty. Speed-curvature relationships
follow the same pattern as speed-density models. Similar results have been witnessed in workload research (de Waard, 1996; Cnossen et al., 2000).

As an improvement on the zero-risk model, Summala (1997) has postulated the theory of behavioural adaptation, which appears to be more in line with driver intervention to manage workload instead of risk control. To explain the speed behaviour of drivers on different sections of a road, the simple case of lane tracking is considered. Here, the painted lane is taken as a tube in which the driver has to guide the vehicle and the controlling measure is the time-to-lane crossing (TLC) as defined by van der Horst & Godthelp (1989). TLC is the momentary time until crossing either of the lane boundaries if the present course is being kept. The driver is constantly trying to maintain this time margin in order to keep the vehicle in the tube. The literature regarding the accuracy with which the human being is able to estimate this time is well documented by Summala (1997).

For an analogy to workload, time margins are compared to the effective time for action in the workload model proposed by Hancock & Caird (1993). In this model, workload increases as the effective time for action decreases. Similarly, ‘decreasing road width or increasing curvature calls for slowing down (or more effort), and wider or straighter road allows higher speeds or more time’ (Summala, 1997). Here, more time or higher road standards are not related to higher speeds by way of maintaining some subjective level of risk. Instead, speed is taken as a means of satisfying both short and long term goals of driving a vehicle. A journey is initiated with the aim of reaching the destination within a
particular time, which controls the target speed. The goal then is to maintain this target speed to meet the essence of the journey, and only when obstacles appear on the road will the driver take corrective actions to control time margins. Whilst this leads to a reduction of the time margins, it could be erroneous to say that the driver increases speed purposefully for this reason. However, it is believed that prolonged exposure to low task situations can lead to driver deactivation (Lamm et al., 1999, Summala, 1997) and drivers might increase speed either consciously or unconsciously in order to reduce the boredom.

The mental effort associated with maintaining time margins can be better explained with a consideration of the mechanism involved. The task of lane keeping or curve tracking requires the driver to continuously make estimates of vehicle position and direction relative to other obstacles on the road (road edges, other vehicles in the traffic, pedestrians, etc.) and to make correct steering actions away from these obstacles. This is done in a cycle with action starting at collecting information on present position PV(t_n) , speed, and direction of the vehicle on the road (at time T=t_n) relative to those of other obstacles which might be stationary or also moving at various speeds. A cognitive ESTIMATOR estimates the future positions, speed/courses (at time T=t_{n+1}), and a COMPARATOR compares the position of the vehicle with those of all other obstacles to see whether the separation is greater than or equal to a safe distance D. If the future separation distance is safe, the driver continues on the present course and speed to position PV(t_{n+1}), and then updates the positions/speeds/courses of all participants and the cycle repeats itself. If the separation is not safe enough, the driver takes adaptive actions and sends the results to the comparator to complete the cycle (Figure 4.5).
Higher speeds mean that this cycle of estimation of vehicle position, and making corrective manoeuvres have to be undertaken at a faster rate in order not to miss the flow of vital information. The driver will need to view the road more frequently to collect information on position, direction and speed of travel of all traffic participants, process this information to arrive at corrective actions in a shorter period of time. This could increase driver mental workload, with the possibility of an eventual increase in road safety problems.

Figure 4.5: The adaptive controller in automobile driving
In most cases, the driver is able to adapt efficiently and can complete the journey without any incidents despite the numerous possibilities. There are however times or situations when the driver will fail to adapt adequately, and accidents may result. Some design situations may cause the driver to adopt speeds that result into workloads that are far in excess of the driver's information processing capacity. The problem for design is to understand how drivers adapt, and how they sometimes fail in adaptation, so that design can be tailored to aid the driver to adapt adequately. A model of driver workload, which considers all the determinants and also includes adaptation, could be the key to the solution of this complex problem.

4.5 DRIVER WORKLOAD MEASUREMENT TECHNIQUES

Having highlighted the main parameters to be used in a predictive model of driver workload, field measurement techniques are also required that may not necessarily be the same as those used in other situations. Driver workload measurement has however derived a lot from other areas where workload has been measured, especially in aviation. The workload literature has identified three main groups of measurements: performance measures, subjective measures, and physiological measures. Driver workload measurement techniques also follow the same pattern and they are discussed below.

4.5.1 Performance Measurements

Task performance measurement techniques are derived from the task of interest. This area of measurement is where one would find a variation from one field of study to another (e.g. nuclear power plant vs. aviation). In driving, task performance measurement
techniques can also be related to the primary task of driving, in which case the variables measured are related to the primary task of driving. They can also be related to a subsidiary/secondary task, which may or may not be related to driving, and such measures are called secondary task measures. A secondary task related to driving is however recommended (de Waard, 1996) in order to reduce the effects of primary task intrusion.

4.5.1.1 Primary Task Performance Measures
Zeeger et al. (1988) suggested that the occurrence of crashes must be considered as the probability of failure by the road, the vehicle and the driver, separately or jointly. The primary task of driving should therefore be the maintenance of a safe driving environment, with the occurrence of crashes being a measure of the extent of failure in this primary task. Crashes are, however, such rare and expensive phenomena that waiting for them to occur before safety studies or interventions take place is giving way to more pro-active safety approaches. For example, as a measure of safety on the road or driver performance, measures of near misses, keeping lane positions, steering wheel movements, speed, time remaining before the road edge is crossed, etc. have been used successfully since poor performance on these tasks are related to crashes (Brookhuis & de Waard, 2001; Kantowitz & Simsek, 2001 (see Table 4.1)).
Table 4.1: Summary of Primary Task Workload Measures (Kantowitz & Simsek, 2001)

<table>
<thead>
<tr>
<th>Study</th>
<th>Workload Measure</th>
<th>Main Effect</th>
<th>Influenced by at least one Secondary Task?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noy (1989)</td>
<td>Standard Deviation of Lateral Position (SDLP)</td>
<td>Not Reported, Curve Type</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Lane Exceedance Ratio</td>
<td>Not Reported, None</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Time to Line Crossing (TLC)</td>
<td>Curve Type, Curve Type</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Headway</td>
<td>Not Reported, Secondary Task Difficulty</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Velocity</td>
<td>Not Reported, None</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>SD Velocity</td>
<td>Not Reported, None</td>
<td>Yes</td>
</tr>
<tr>
<td>Verwey &amp; Veltman (1996)</td>
<td>Speed</td>
<td>None, Not Reported</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Steering Wheel Reversal Rate</td>
<td>Presence of Loading Task, Not Reported</td>
<td>Yes</td>
</tr>
<tr>
<td>Verwey (1991)</td>
<td>Speed</td>
<td>Driving Situation, Traffic Density</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation of Speed</td>
<td>Driving Situation, Traffic Density</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Steering Wheel Action Rate</td>
<td>Driving Situation, Traffic Density</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The use of speed as a measure of performance in any workload environment may be questionable, since speed itself appears to be a determinant of workload. When time constraint is not a factor of workload, speed may show a variation of workload. Speed comes out as a control mechanism for driver workload because it is often under the control of the driver. At the times when it leaves the control of the driver, higher speeds could be interpreted as high performance whilst the driver could be experiencing high workloads. This makes speed alone unsuitable as a driver workload measure.
4.5.1.2 Secondary Task Performance Measures

The best secondary task measures are those which are not alien to the task, and would therefore not intrude on the primary task (de Waard, 1996). For the driving situation, car-following (delay to speed adaptation to a lead car’s speed changes) and mirror checking satisfy this condition. Other secondary task measures that have seen wide application in driver workload measurement were recorded by Kantowitz & Simsek, (2001) as presented in Table 4.2: In driving, there is also a safety concern for the introduction of a subsidiary task, which might take away attention from the primary task of driving (primary task intrusion). Primary task intrusion can be reduced with the use of secondary tasks that are part of the task at hand. Mirror checking is one such task that is not alien to the driving task.

Another measure that has seen widespread application recently is the visual occlusion technique. Green & Tsimhoni (2001) have outlined its usefulness from its origin in experiments conducted by Senders et al. (1967) to the present day. Research by Sabey & Staughton (1975, cited by Lansdown, 2001) has shown that more than 90% of the information required for driving is acquired through vision. To put it in simpler terms, Green & Tsimhoni (2001) write, “Driving is a visual task. If the vehicle operator cannot see, they cannot drive”. The driver’s performance on the primary task of driving would therefore depend on visual resources, and measurements on driver visual behaviour should give an indication of the information needs/content of the driving task. Driver visual behaviour has been measured in terms of fixation/glance duration, and glance frequency. Increased glance durations have been found to have a direct bearing to high
operator workload (O’Donnell & Eggemeier, 1986). When the primary task of driving is not demanding much of the driver’s visual resources, spare capacity is used to attend to secondary tasks, hence the high use of visual detection as secondary task measures (Table 4.2).

**Table 4.2: Summary of Secondary Task Workload Measures (Kantowitz et al., 2001)**

<table>
<thead>
<tr>
<th>Study</th>
<th>Workload Measure</th>
<th>Main Effect</th>
<th>Influenced by Primary Task?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noy (1989)</td>
<td>Perception Task Reaction Time</td>
<td>Not Reported</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Memory Task Reaction Time</td>
<td>Not Reported</td>
<td>None</td>
</tr>
<tr>
<td>Verwey (1991)</td>
<td>Visual Detection (reduction of % detected due to driving)</td>
<td>Not Reported</td>
<td>Not Reported</td>
</tr>
<tr>
<td></td>
<td>Visual Addition (reduction of % correct due to driving)</td>
<td>Not Reported</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Auditory Addition (reduction of % correct due to driving)</td>
<td>Not Reported</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Direct measures of glance duration include the use of video camera registration or registration by the ElectroOculoGram (EOG). This type of measurement tends to remove eye fixation measures from the region of secondary task measures to one of physiological measures. A direct measure of driver visual demand is done through the use of visual occlusion techniques. The driver’s vision is occluded either by natural means like closing of the eyes, or by artificial means using occlusion devices, and performance on the driving task is measured. Artificial devices used in visual occlusion experiments have included motorcycle helmet visors, windshield wiper in heavy rain, LCD goggles, LCD
face shields, full windshield LCD to turning of the headlight during night driving. The idea has its origin from experiments conducted by Sender et al. (1967) where they reported as follows:

"Some of our theoretical notions arose from some personal observations made by the senior author while driving on a straight road with little oncoming traffic. A heavy rain resulted in the windshield wipers being able to clear only a small sector of about 20 degrees behind the blade, so that visual conditions for the driver were somewhat analogous to those which would be presented by a radar sweep. The wiping speed was independent of the speed of the car. The driver became somewhat aware of a psychological speed limit. Up to that speed, there was no anxiety; above that speed the driver became anxious and had to slow down." (Senders et al., 1967, 16)

The visual occlusion technique of measuring driver workload has been used more frequently in recent times as one of the means of measuring the demands of in-vehicle information systems on driver performance (Green, 1999; Green & Tsimhoni, 1999; Tsimhoni et al., 2002). The technique has also been used to measure the demands of road layout on driver performance (Wooldridge et al., 2000, Green & Tsimhoni, 1999).

4.5.2 Subjective Measurements

There are very few subjective measures of workload that are specific to the driving situation. Already mentioned in this report is the work of Messer et al. (1981), wherein
road safety experts developed subjective ratings for various road features. These ratings and the underlying theory were successfully used to estimate driver workload in a couple of case studies (Messer, 1980; Krammes & Glascock, 1992; Wooldridge, 1994).

Another specific measure worthy of mentioning is the Road Environment Construct List (RECL, Steyvers et al. 1994). The RECL is a three-factor scale developed to appraise the road environment. The "Hedonic value" is the factor that appraises the aesthetics of the road and its environment whilst the "Perceptual Variation" appraises the heterogeneity of the road environment. Useful to the measurement of driver workload is the factor that deals with the Activation value of the road and its environment.

Other subjective measures that have been used in the measurement of driver workload are those derived from other applications. These include the NASA Task Load Index (TLX, Hart & Staveland, 1988), the Subjective Workload Assessment Technique (SWAT, Eeid et al., 1988), and the Rating Scale Mental Effort (RSME, Zijlstra & Van Doorn, 1985).

4.5.3 Physiological Measures

Physiological measures in driver workload assessment have generally followed what is available for workload assessment elsewhere. ElectroCardioGram (ECG) measures of heart rate, heart rate variability, and 0.1 Hz component of heart rate variability have been used by de Waard (1996) in driver workload measurement with comparable results.
4.6 CONCLUSIONS

This chapter reviewed the concept of workload and its assessment as it is applied to the driving situation. It is apparent that the same problems that plague the assessment of workload in general were inherited together with all the good aspects. This means that driver workload assessment also requires an assessment of all the determinants that account for it and they include:

1. driver state (motivation, fatigue, alcohol/drugs)
2. road complexity which should include geometric design (radius, intersections, roadway width), weather conditions, traffic, and in-vehicle information systems
3. operating speed
4. driving strategies

Methods of measurement or prediction should include all these factors if the theory of driver workload is to be used for design purposes. This may not be possible for all the determinants, but effort should be made to at least include the measurable aspects. Speed is one such measurable parameter that needs special attention in driver workload assessment. Its use as an adaptive strategy should also be modeled in order to come any closer to accounting for driver workload to the fullest.
CHAPTER 5

A DRIVER WORKLOAD MODEL

5.1 BACKGROUND

A model is an abstract representation of a system or a process, which can be used to account for the behaviour of the system, and also to generate testable hypothesis supported by the system, or process (Sanders & McCormick, 1993). A good model of workload should be able to predict workload and its effects on human performance. Armed with a good predictive model, system designers should be able to design so that the operator is not overloaded.

The literature is rife with models, but many of the models have been criticised as a result of poor predictive power, or lack of validity. According to Nygren (1991), many models show little predictive or concurrent validity and others have used correlations with other unvalidated measures of workload as test of validity. This trend has been blamed on the lack of any theoretical consideration in model formulations (Hendy et al., 1997; Hancock & Caird, 1993; Hancock & Chignell, 1988). Nygren (1991) points out that some workload models have mentioned nothing about the hypothetical construct of workload, nor did they relate it to human information processing.

Recent road safety practices, which can best be explained in terms of human information processing theory, have been driven by common sense and empiricism. These include design consistency considerations and road safety audits. Design consistency
formulations were developed intuitively; first, based on the fact that drivers do not always drive at the design speed when most sections of the road allow them to drive at speeds higher than the design speed. Drivers are therefore likely to exceed their desired speeds on restrictive sections of the road that are placed adjacent to unrestricted sections. The implications of this are twofold: (1) higher speeds can result in exceeding the physical limits of driving, since the laws of the vehicle dynamics of safety (skidding out on curves, rollover, stopping sight distance, etc) are guided by the operating speed, (2) since driving involves receipt and processing of information, higher speeds would require a higher rate of information processing. Secondly, since speed differences appear to be the problem in design consistency, empirical evidence was compared with accident occurrence and the agreement came out easily. This does not however preclude the search for a theoretical explanation. The fact that it has worked seems to suggest an underlying theory that should serve road safety in other areas.

Finding a theoretical explanation, however, requires answers to some pertinent questions. What does design inconsistency do to the driver? It has been identified as a violator of driver expectation (Anderson et al., 1999; Krammes et al., 1992). How does driver expectation lead to errors? Driver reaction time may increase (Johannsen et al., 1971), that is, more time may be required to perceive information and act on it. The driver cannot just mobilize enough resources under unexpected situations to cope with information processing requirements. Therefore, there is pressure on limited resources resulting in high workloads and errors. The theoretical link seems to be connected in part to human information processing theory; limitations of the human information processing
capacity and its relationship to driver workload, which is not so explicit in design consistency applications.

5.2 DRIVER WORKLOAD MODELS

The problems associated with prediction in the general workload application are very much present in the field of driver workload. So far, most of the research reviewed in driver workload has been directed at showing sensitivity of workload with the various components of workload, especially road complexity (de Waard, 1996; Wooldridge et al. 2000), which does not imply prediction. Although most measures of driver workload examined have directly used models in the general literature, models should be tailored or adjusted to reflect the components of driver workload and how these components combine to load the driver.

It is difficult to talk specifically about driver workload models because there have not been many of them. However, considerable work has been done on driver behaviour modeling, either for operational reasons or for safety, and with some adjustments some of the models may be transformed into driver workload models. A recent example is the work of Summala (1996, 1997), which uses the principles of the zero-risk model (Naatannen & Summala, 1974, 1976) to explain driver behaviour in terms of workload management strategies. With this possibility, it may not be 100% correct to say that driver workload models are few.
Except for the risk models that treat driving as a self-paced task, cognitive aspects of the driver were absent from most models reviewed. As in other human factors applications, driver behaviour models were throughput, treating the driver as a black box with only input-output considerations. The processes that transform inputs into outputs are mediated by the cognitive control structure of driver behaviour. When these processes are added as suggested by Michon (1985), performances failures can easily be related to cognitive bottlenecks.

Previous chapters have dealt with various techniques of measuring workload including specific measurements of driver workload. Much research has already been invested in finding measures of workload and the practice is not short of measurement techniques. It is indeed important to measure driver workload but what is more important for design purposes is the ability to predict it. Highway engineers have associated driver workload to geometric design either by way of the complexity of design features (Lunenfeld, 1993) or by design practices (Messer et al., 1981; Kanellaidis & Sakki, 1997) related to inconsistent design and violation of driver expectancy. This connection prompted measurement interests as well as the development of predictive models. Because of the theoretical foundation and/or the consideration for speed, the models of Senders et al. (1967), Messer et al. (1981), and that of Hules et al. (1989) are worthy of mention.

5.2.1 Senders et al. Model

This model looks at the information needs of the driver when traversing different sections of a road. As stated in the previous chapter, the theoretical foundation of the model was a
result of personal observations of one of authors (Senders, et al., 1967). From these observations, the situation on the road was equated to signal sampling theory in which the rate of sampling for signal reconstruction is related to the bandwidth of the signal. In the case of the road, the sampling rate, or rather the attention demand is a function of the characteristics of the road and the speed at which the road is traversed. The characteristics of the road determine the amount of information that is stored into it, and the rate at which this information is presented to the driver depends on the speed. Forming the basis of occlusion experiments, the model is in terms of driver uncertainty at the end of an occlusion interval. If, for a homogeneous section of a road, the amount of information could be expressed as bits of information per mile, then the amount of uncertainty regarding vehicle position and the position of other objects on the road increases with the length of occlusion interval. Having defined information as the knowledge or news that reduces ones uncertainty or the probability of being correct about the true state of affairs (Park, 1987), then the longer the occlusion time, the more information required to be processed by the driver.

A driver who is driving in a busy built-up area is required to look more often at the road than one who is driving on a straight rural road because of the difference in information contents of these roads. Also, as the bendiness or the hilliness of the road increases, so also does the frequency of glances at the road as the information needs of the driver increase with the complexity of the road. Traversing the road at a higher speed would also mean that more information is required to be processed per unit of time. If however
the rate at which the driver can process information is limited, then the driver would choose a speed which would correspond to his/her optimum information processing rate.

The amount of driver uncertainty (or information needs) at the end of an occlusion interval was thus expressed in the following model which combines the information density of the road and the speed (Senders, et al., 1967).

\[ U(T_d) = H*D[1-e^{(V/D + 1/FT_d)}] + K_n V^2 (T_d)^{3/2} \]  \hspace{1cm} (5.1)

Where

\[ U(T_d) = \text{uncertainty at the end of the occlusion interval } T_d \]

\[ H = \text{information density of the road in bits per mile} \]

\[ D = \text{weighting constant per mile} \]

\[ F = \text{forgetting rate parameter} \]

\[ V = \text{velocity in miles/second} \]

\[ K = \text{constant} \]

The driver is said to adjust occlusion time or speed so that the uncertainty does not exceed a certain critical level \( U_c \), which corresponds to driver capacity so that

\[ U(T_d) \leq U_c \] \hspace{1cm} (5.2)

Recent literature has seen widespread use of the occlusion technique as a measure of driver workload. The problem with most of the measurements, however, is that the consideration of speed as one of the variables is not so explicit.
5.2.2 Messer et al. Model

The Messer et al. (1981) model, which has been discussed under subjective workload measurements, is another model based on the workload construct as it applies to the road environment. Road complexity was given subjective ratings ranging from zero (meaning no problem) to 6 (critical problem), as shown in Table 5.1.

Table 5.1: Summary of geometric feature ratings for average conditions on various classes of rural non-freeway highway conditions (Messer et al., 1981).

<table>
<thead>
<tr>
<th>Geometric feature</th>
<th>two-lane</th>
<th>four-lane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>high</td>
<td>mediocre</td>
</tr>
<tr>
<td><strong>Bridge</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>narrow width, no shoulder</td>
<td>5.4</td>
<td>5.4</td>
</tr>
<tr>
<td>full width, no shoulder</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>full width, with shoulder</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Divided highway transition</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-lane to 2-lane</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-lane to 4-lane</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lane drop (4-2 lanes)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>intersection</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unchannelized</td>
<td>3.7</td>
<td>2.8</td>
</tr>
<tr>
<td>Channelized</td>
<td>3.3</td>
<td>2.5</td>
</tr>
<tr>
<td>rail road crossing</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td><strong>shoulder width change</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>full drop</td>
<td>3.2</td>
<td>2.4</td>
</tr>
<tr>
<td>Reduction</td>
<td>1.6</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Alignment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reverse horizontal curve</td>
<td>3.1</td>
<td>2.3</td>
</tr>
<tr>
<td>horizontal curve</td>
<td>2.3</td>
<td>1.7</td>
</tr>
<tr>
<td>crest vertical curve</td>
<td>1.8</td>
<td>1.4</td>
</tr>
<tr>
<td>lane width reduction</td>
<td>3.1</td>
<td>2.3</td>
</tr>
<tr>
<td>crossroad overpass</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>level tangent section</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

0 = no problem, 6 = critical problem
The above ratings could be seen as expressing the complexity of various road features of the road as interpreted by the expert eye. It should be related to the amount of information embedded in the segments having the features. The final workload which the driver experiences was given by (Messer et al., 1981).

\[ WL_n = U \times S \times E \times R_f + C \times WL_{n-1} \]  

Where

- \( WL_n = \) workload at the feature
- \( U = \) driver unfamiliarity factor \((0.4 < U < 1)\)
- \( S = \) sight distance factor \((0.6 < S < 1.8)\)
- \( E = \) feature expectation factor \((E = 1 \text{ if feature is not similar to } (n-1) \text{ feature, otherwise } E = 1 - C)\)
- \( R_f = \) workload rating as per Table 5.1
- \( C = \) feature carryover factor \((0 < C < 1, \text{ depending on the distance between features})\)
- \( WL_{n-1} = \) workload value for preceding \( n-1 \) feature.

The Messer et al. model seems to have gone a long way to consider the practical implications of a model of driver workload. The workload, which a driver experiences depends on the complexity of the road features, driver unfamiliarity, feature expectancy, and sight distance.

The factor for unfamiliarity is a function of road type, with rural principal arterial roads having the highest factor of 1. The lowest factor, 0.4 is assigned to rural local roads of the farm-to-market road type on which mostly familiar drivers would drive. The sight distance, the feature expectancy, and the carryover factors are functions of the 85th
percentile speed on the approach feature. They are determined from charts which show higher parameter factors for higher 85\textsuperscript{th} percentile speeds. The significance of the dependence of these factors on the approach speed of the 85\textsuperscript{th} percentile driver has both physical and cognitive implications. Similar to the effect of operating speed in the Senders et al. (1967) model is that the higher the approach speed, the higher the probability of traversing the feature at a higher speed. This should increase the information processing requirements of the driver, hence higher workloads.

As a tool for evaluating design consistency, it included criteria for consistent design given in Table 5.2 below

Table 5.2: Driver workload based on level of consistency criteria (Messer et al. 1981)

<table>
<thead>
<tr>
<th>Driver Expectation</th>
<th>Level of Consistency</th>
<th>Workload Value (WLn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Problem Expected</td>
<td>A</td>
<td>≤1</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>≤2</td>
</tr>
<tr>
<td>Small Surprises possible</td>
<td>C</td>
<td>≤3</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>≤4</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>≤6</td>
</tr>
<tr>
<td>Big problems possible</td>
<td>F</td>
<td>&gt;6</td>
</tr>
</tbody>
</table>

5.2.3 Hules et al. Model

Based on knowledge about road features that are likely to cause attentional demand problems to drivers, Hules et al. (1989) developed an objective model that could be used to estimate the attentional demand of road segments. The contributions of sight distance (A), curvature (B), lane restriction (C), and road width (D) to attention demand (Q) were modeled in an equation given by

\[ Q = A + B + C + D \]

(5.4)

The contribution of each feature to the road segment attention demand ranged from zero (lowest possible effect) to 100 as follows:
Sight distance: \( A = 20 \log_2 \left( \frac{500}{S_D} \right) \)..............................................................(5.4a)

Where \( S_D \) is the sight distance in meters, \( A = 0 \) for \( S_D > 500 \)m, and \( A = 100 \) for \( S_D < 15.6 \)m.

Curvature: \( B = R^{-1} \left( \frac{100}{(R^{-1})_{\text{max}}} \right) \)..............................................................(5.4b)

Where \( R \) is the radius of the curve, \((R^{-1})_{\text{max}}\) was set at 0.054/meter for which \( B \) will be equal to 100.

\( C = -40S_0 + 100 \) ..............................................................(5.4c)

Where \( S_0 \) is the distance to the closest obstruction to the road in meters, \( C = 0 \) for \( S_0 \geq 2.5 \)m

\( D = -36.5R_w + 267 \) ..............................................................(5.4d)

Where \( R_w \) is the road width in meters, \( D = 0 \) for \( R_w \geq 7.3 \)m, and \( D = 100 \) for \( R_w \leq 4.65 \)m.

To test Equation 5.4, the authors made experts rate 186 road segments on a subjective scale of 1 (no problem) to 9 (very high visual demand). A comparison of the ratings with the results of the model showed a reliable correlation \((R^2 = 0.73, \ p = 0.0001)\). Other validation experiments (reported by Kantowitz & Simsek, 2001) however showed mixed results.

The inclusion of sight distance in the model seems an important step towards the inclusion of driving speeds. However, it fails to capture driver speed behaviour at the various road features since the sight distances do not relate to the features specifically.

5.2.4 Summala Model

Important aspects of Summala's (1996, 1997) model of behavioural adaptation have already been highlighted in Paragraph 4.4 (Driver Adaptation) of this thesis. Although
this model still needs to be developed into a predictive/mathematical model of driver workload, the theoretical formulation is worth mentioning. The model gives a clear understanding of the effects of time margins as this relates to operating speeds and driver workload.

Figure 5.1: “Driver task cube” outlining basic dimensions of the driver’s task relevant to modeling of behavioural adaptation (Summala, 1997).
Figure 5.2: The role of time and speed in modeling behavioural adaptation (Summala, 1997).
The basic concepts of Summala’s model of behavioural adaptation in driving combines the basic tasks of driving with hierarchical classifications of driver behaviour in an information processing model as shown in the driver task cube of Figure 5.1. The three dimensions of the model include: (1) a functional hierarchy starting from vehicle control to vehicle choice, (2) a functional taxonomy of driver behaviour dealing mainly with guidance level tasks, and (3) information processing with a distinction between automated control and conscious decision making control. The role of speed in the model as explained elsewhere in this report is illustrated in Figure 5.2.

5.3 PROPOSED DRIVER WORKLOAD MODEL

Kantowitz & Simsek (2001) have argued that the main obstacle to the assessment of workload is the weak link between theoretical models of workload and operational definitions. The literature has shown ample evidence suggesting that workload has three principal dimensions, namely: task complexity, time constraint, and psycho/physiological aspects (Hendy et al., 1997; Rex, 1988; Reid et al., 1988). These principal dimensions are also mediated by the intervening ability of the operator. For the driving task, the time constraint aspect is translated into the operating speed that the driver chooses.

The models described in Paragraph 5.2 above can be said to have some consideration for speed by implication to some of the variables considered such as sight distance. The absence of a direct link to speed however severs the link with the operational definitions of workload. Engineers would like to deal with parameters like sight distance, radius of curvature, roadway width, etc., but according to Kantowitz & Simsek (2001), the lack of
a direct consideration for speed in relation to its effect on time margins leaves a weak link to workload. Models require this link in order to assure a strong theoretical basis, and easy adaptation to other areas. This according to Kantowitz (1992), prevents "re-invention of the wheel" when circumstances differ (e.g., on-line design versus off-line design). The driver workload model proposed in this thesis combines the principal dimensions of road complexity, operating speed, and psycho/physiological aspects of the driver, with the driver's speed management strategy to arrive at a model of driver workload that is more in line with the definition of workload. It is a first step towards the development of a model, which considers the theoretical implication of operating speed with regards to time margins in driver workload formulation.

5.3.1 The concepts of the model

Central to this model, like most other human information processing models is the limited information processing capacity of the driver. In line with the information processing model of Hendy et al. (1997) and the underlying principles of the latest Summala (1997) model, driver workload is assumed to be driven by load intensity imposed by the road environment and time margins imposed by operating speed. Referring to Figure 3.6 and the foregoing analysis in the Senders et al. (1967) model, a road section can be assumed to contain a certain amount of information per kilometre of its length. Let this information level for a particular road section be $B_r$ bits/km.
Given that the driver can process information at a maximum (or some optimal level relating to motivation) of \( C \) bits/sec, then the time \( T_r \), required to process this information is given by

\[
T_r = \frac{B_r \text{ bits/km}}{C \text{ bits/sec}} = \frac{B_r}{C} \text{ sec/km} \tag{5.5}
\]

That is, the driver should traverse a kilometre of the road in \( \frac{B_r}{C} \) seconds (or more). \( T_r \) is the reciprocal of the speed at which the driver should traverse this road section without overloading the driver.

\[
T_r = \frac{1}{V_r} \text{ sec/km} \tag{5.5a}
\]

\( V_r \) being the required speed.

If for any reason (e.g. design inconsistency), the driver traverses the road at a speed of \( V_a \) km/sec, then the time available, \( T_a \), to process this information will be

\[
T_a = \frac{1}{V_a} \text{ sec/km} \tag{5.5b}
\]

The information processing load or time pressure (TP) will be given by

\[
TP = \frac{T_r}{T_a} = \frac{1}{V_r} + \frac{1}{V_a} = \frac{V_a}{V_r} \tag{5.6}
\]
TP in this case can also be alternatively expressed in terms of relative demand for processing resources. The rate of information processing demand (RID) can be expressed as the ratio of the total information and the time available to process it.

\[
\text{RID} = \frac{B_r}{T_a} = B_r \cdot V_a \text{ (bits/km * km/sec)} \tag{5.7}
\]

\[
\text{TP} = \frac{T_r}{T_a} = \frac{1}{C} \cdot \frac{B_r}{T_a} = \frac{B_r \cdot V_a}{C} = \frac{\text{RID}}{C} \tag{5.8}
\]

Equation 5.8 is a simplified version of Equation 5.2 in the Senders et al. (1967) model. Traversing the road section at a higher speed means that more information is required to be processed by the driver, which also corresponds to the resolution of high levels of uncertainty. Also in this case, channel overload occurs when TP>1, (or rather when RID>C), or in terms of Equation 5.6, when \( V_a \), the available speed is greater than the required speed, \( V_r \). The required speed is the limiting speed above which the driver's information processing capacity is exceeded for a particular road section.

Again referring to Figure 3.6, when TP>1, the operator would normally invest effort in order to reduce the mismatch in three ways: (1) by increasing the channel capacity (C); (2) by reducing the load intensity (B_r); or (3) by making more time available. Except for variations in operator state such as fatigue, anxiety, motivation, etc, which might affect capacity, channel capacity is assumed to be constant. This leaves only two options to the driver for reducing the mismatch between the Rate of Information Demanded (RID) and
capacity. Adaptation, the process by which the operator reduces this mismatch has already been discussed (in general terms as well as in driving). Speed being the main control element, drivers probably will reduce their operating speeds in order to reduce this mismatch.

Since TP is the main determinant of errors and performance, correlations can be investigated between TP and other performance functions. Variables in the analysis will be road complexity and speed. A common road complexity that is associated with road safety is the degree of curve (D), and fortunately it is measured on a per kilometre basis, either in degrees/km or gon/km (measure of curvature). Another measurable road complexity is the K value of vertical curves, which is the length of curve per percent change in A (the algebraic difference in grades). It has been shown how other measures of road complexity are measured per kilometre length of the road. This research will first of all try to investigate the use of this model with respect to degree of curve, since the accident rate on horizontal curves is in the range of 2 to 5 times that on tangent sections on two-lane rural highways (Lamm et al., 1997).

So, for a curved section having a curvature of D degrees/km, the information load \( B_r \) bits/km can be expressed as a function of D, that is, \( B_r = f(D) \). Then TP will be given by

\[
TP = \frac{T_r}{T_a} = \left( \frac{1}{C} \right) \frac{B_r}{T_a} = \frac{f(D) \cdot V_a}{C} \quad \text{........................................... (5.9)}
\]

or

\[
TP = \frac{f(D \cdot V_a)}{C} \quad \text{........................................... (5.9a)}
\]
For a relationship between the dependent variables of driver performance, errors, workload, and the independent variable of Time Pressure TP, reference is made to Figures 3.7 and 5.2. Driver workload can be expressed as

\[
\text{Driver workload } WL = f(TP) \tag{5.10}
\]

and since driver performance and driving errors are a function of driver workload, the following relationship can be formulated

\[
\text{Driving Errors} = f(TP) \tag{5.10a}
\]

The rate of information processing demand (RID) of the driving task, which is best measured in terms of bits/sec, can now be expressed as function of the product of speed and density of road complexity, measured in degrees/sec or other measure of road complexity per second. Since driver processing capacity is assumed to be a constant, driver workload and driving errors can also be expressed as a function of the rate of information processing demand (RID). Measures of driving performance should be shown to increase with increases in speed and road complexity. For design purposes however, the designer is interested to know the limits to which the driver can be loaded in order to avoid exceeding the limits. The answer to this question can be found in driver behaviour modeling, since driving has already been established as a self-paced task. Driving should normally be an error-free task as long as adaptive strategies work in keeping RID within limits.
Having posited that RID depends on road complexity and speed, and it is managed with speed, a combination of the model of RID with driver speed behaviour (models) should show the limits to which the driver operates in this self-paced task.

5.3.2 Speed models

The modeling of driver speed behaviour has been of interest to road safety practitioners for over 30 years now, since the realization that the design speed concept caused drivers to choose speeds, which might introduce critical driving manoeuvres. The speed that a driver chooses may be influenced by legal speed limits, weather conditions, and the presence of other vehicles, but in the absence of these factors, the speed at which the driver operates his/her vehicle is highly influenced by the physical characteristics of the road. The American Association of State Highways and Transportation Officials (AASHTO, 1994) defines operating speed as “the highest overall speed at which a driver can travel on a given highway under favourable weather conditions and under prevailing traffic conditions without at anytime exceeding the safe speed as determined by the design speed on a section by section basis”. For design purposes, the operating speed of the 85th percentile driver has been recommended and consistent design aims at harmonizing the 85th percentile speeds of drivers as they move from one design feature of the road to another.

Many models on the relationship between the 85th percentile speed and various road design parameters have been developed over the years. Equation 5.11 shows the outcome of a research that investigated the influence of road design parameters (degree of curve,
curve length, superelevation rate, lane width, shoulder width, gradient, posted speed) and traffic volume on the 85th percentile speed on 261 two-lane rural roads in New York State (Lamm et al., 1989).

\[ V_{85} = 34.700 - 1.005DC + 2.081LW + 0.174SW + 0.0004AADT \]

\[ R^2 = 0.842 \] (5.11)

Where \( V_{85} = 85^{th} \) percentile speed (mph)

\( DC = \) Degree of curve (degree/100ft)

\( LW = \) Lane width (ft)

\( SW = \) Shoulder width (ft)

\( AADT = \) Average Annual Daily Traffic

The effects of sight distance, curve length, and gradient were not significant in the explanation of the variability of \( V_{85} \), so they were not included in the equation. A comparison of the correlation coefficient of the above equation with that of a regression analysis relating \( V_{85} \) to the degree of curve alone (Equation 5.12) shows that most of the variation in \( V_{85} \) can be explained by the degree of the curve (the other variables accounted for only 5.5% of the variability in the estimated 85th percentile speed).

\[ V_{85} = 58.656 - 1.135 DC, \quad R^2 = 0.787 \] (5.12)

An earlier study by Taragin (1954) also revealed that compared to other design parameters; the degree of curve has the greatest influence on the 85th percentile speed.
(with pavement width also having an influence to some extent). A similar investigation by Lin (1990) showed the degree of curve accounting for 87% of the variation in 85th percentile speeds, whilst lane width accounted for only 4%.

![Curvature Change Rate for a single curve - CCRs (gon/km)](image)

Figure 5.3: Operating Speed Backgrounds for Two-Lane Rural Roads in Different Countries (Lamm et al., 1997).

With accident data showing an over representation of mishaps on curved sections (Lamm et al, 1992, 1997), road safety engineers have blamed road mishaps on improper speed behaviour of drivers on curves. This somehow explains the reason for the numerous studies on driver speed behaviour on curved sections. The general form of this behaviour is shown in Equation 5.12, and also in Figure 5.3.

5.3.3 Accident Experience and Time Pressure

Starting from a definition of workload derived from the human information theory, an expression for the Time Pressure (TP) experienced by the driver has been developed. The various forms of this expression of Time Pressure in Equations 5.6, 5.8, and 5.9a are shown here in Equation 5.13.
\[ TP = \frac{T_r}{T_a} = \frac{V_a}{V_r} = \frac{B_r V_a}{C} = \frac{f(D V_a)}{C} \]  \hspace{2cm} (5.13)

In terms of information theory, TP in its various forms is the ratio of the rate of information demanded (\(RID = B_r V_a\)) on the driver, and the driver’s information processing capacity (\(C\)). This represents the exact definition of workload, and if theory is correct, then measures of driver workload and driver performance should be seen to correspond to the various expressions of TP.

Various research experiments that have already been discussed in this report have shown how driver workload varies with increases in road complexity (especially the degree of curve) and the operating speed of drivers (Cnossen et al., 2000; Senders et al., 1967; McDonald et al., 1975). The connection between expressions of TP and driver performance, and in particular, accident experience is found in design inconsistency and its relationship to crashes. One way of ensuring design consistency is to design so that the speed at which a driver would normally traverse a section of road, as represented by the 85\(^{th}\) percentile speed is not exceeded. The potential for exceeding this speed arises when the road section in question is placed downstream of another section whose 85\(^{th}\) percentile operating speed is far in excess of that of the section being analyzed. When this happens, large speed reductions are required, and accident experience has been found to be related to the magnitude of speed reduction (Lamm et al., 1999). One design consistency criterion has been to keep the difference between the 85\(^{th}\) percentile speeds of
adjacent road sections to a minimum, and the other one is to minimize the difference between the design speed and the operating speed (see Table 5.3).

Table 5.3: Ranges of Safety Criteria for Good, Fair and Poor Design Practices (Lamm et al., 1999)

<table>
<thead>
<tr>
<th>SAFETY CRITERION</th>
<th>GOOD</th>
<th>FAIR</th>
<th>POOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>(</td>
<td>V_{85_i} - V_{85_{i+1}}</td>
<td>\leq 10\text{km/hr})</td>
</tr>
<tr>
<td>II</td>
<td>(</td>
<td>V_{85} - V_{85_d}</td>
<td>\leq 10\text{km/hr})</td>
</tr>
</tbody>
</table>

Where \(V_{85_i}\) is the 85\(^{th}\) percentile speed of the \(i^{th}\) section and \(V_d\) is the design speed.

Already \(V_r\) (in Equations 5.6 and 5.13) has been defined as the speed at which the driver can traverse a given road section without overloading his/her information processing capacity. Design consistency practice also recommends that the 85\(^{th}\) percentile operating speed at a section should not be exceeded (Lamm et al, 1999). Without the consideration for exceeding human information processing capacity, the only plausible engineering explanation for accident causation when the 85\(^{th}\) percentile operating speed is exceeded would be skidding out on curves. Since research has also shown that speeds higher than the required speed can cause driver overload, then another mechanism by which accidents occur would be an increase in driver workload as a result of speeds in excess of the required speed.

Observed speeds of individual drivers should correspond to their required speeds, \(V_r\), since these are speeds freely chosen by the driver. Design consistency analysis uses the
observed speed of the 85th percentile driver (V85) in order to account for a majority of the drivers. There is however no explanation of the mechanism by which the driver chooses to drive at V85. One plausible explanation then, relates to the information processing capacity of the driver. By analogy, the only means by which the available speed \( V_a \) in Equations 5.6 and 5.13 will exceed \( V_r \) is through the 85th percentile speed on the upstream section of road.

As a corollary to Equation 5.6, Time pressure TP can also be expressed as the difference between \( T_r \) and \( T_a \) (Benson III et al, 1998). In that case Time Pressure TP is also given by

\[
TP = T_r - T_a = V_a - V_r \tag{5.14}
\]

This is synonymous with the design consistency practice which has related accident experience to the difference between speeds instead of the ratio of speeds. Notwithstanding the above, it is worth noting that studies in Russia (Tsyganov, 2001) showed a high correlation between accident experience and the ratio of the 85th percentile speeds of adjacent sections given by

\[
\frac{V_{85_i}}{V_{85_{i-1}}}
\]

where: \( V_{85_i} = 85^{th} \) percentile speed on the investigated highway section

\( V_{85_{i-1}} = 85^{th} \) percentile speed on the upstream consecutive section

The same study also developed design consistency criteria which gave restrictions on this ratio.
The above explanations seem to suggest that a theoretical basis of design consistency practice may well have its roots in human information processing theory. Design consistency practice like most human factors practices (Kantowitz, 1992), was derived mainly based on empirical evidence. As discussed elsewhere in this report, a theoretical understanding is necessary in order to prevent a re-invention of the wheel in a similar situation.

5.3.4 The Model

Despite the importance of the workload concept in the design and operation of man-machine systems, human factors experts have found it difficult to produce models with the kind of predictive power needed for design. Workload is a multidimensional construct; as such any model developed to predict it must be founded in a theory that has direct relevance to the various components, just like any other measure of workload. The model should show a monotonic trend with respect to workload.

The theory and measurement of driver workload have indicated that it is affected by road complexity, operating speed, driver information capacity, and driver adaptation. As the speed increases for a particular road complexity, the rate of information processing demand (RID) on the driver increases. This increase in RID should be sufficient to signal increase in driver workload, but the designer needs to know the level of driver loading with respect to driver capacity, which is guided by the adaptive strategies adopted by the driver at various stages of the driving process. A model for the prediction of driver workload, which should also be useful for design purposes, should combine road
complexity, operating speed and driver adaptation. The following analysis shows how this can be done in a more inclusive model of driver workload.

The rate of information demand (RID) has been shown to be a function of the product of speed and degree of a curve. It can also be expressed as the product of speed and other measures of road complexity, which are also mostly measured in terms complexity per kilometre. Equivalent measures can therefore be established as a result. For an analysis dealing with the degree of curve

\[
RID = f(D \times V_a) \quad \text{(5.15)}
\]

\[
RID = DV_a/c \quad \text{(5.15a)}
\]

where as defined before

\[D = \text{the degree of curve (degrees/100m)}\]
\[V_a = \text{the available operating speed on the curve (km/hr), and}\]
\[c = \text{a constant}\]

The general form of driver speed behaviour as shown in Equation 5.12 and the various curves in Figure 4.3 is

\[
V_{85} = A - b \times D \quad \text{(5.16)}
\]

where

\[V = 85^{\text{th}} \text{ percentile speed (km/hr)}\]
D = degree of curve (degrees/100m)

A = a function representing the maximum V85 on tangents

b = constant

Equation 5.16 can be rewritten as

\[ V = aV_{\text{max}} - bD \] \hspace{1cm} (5.16a)

where

a = driver attitude (motivation, goals, skills, etc)

\[ V_{\text{max}} \] = maximum speed (km/hr)

b = \[ aV_{\text{max}}/D_{\text{max}} \]

\[ D_{\text{max}} \] = maximum degree of curve (degree/km) beyond which \( V = 0 \)

For a successful speed management strategy by the 85th percentile driver, \( V_a = V \).

So setting \( V_a = V \) in Equation 5.15, Equations 5.15 and 5.16 can be combined to give

\[ \text{RID} = \frac{(aV_{\text{max}} - bD)D}{c} \] or

\[ \text{RID} = \frac{aV_{\text{max}}}{c} \left( D - \frac{D^2}{D_{\text{max}}} \right) \] \hspace{1cm} (5.17)

Similarly, by substituting for D

\[ \text{RID} = \frac{D_{\text{max}}}{c} \left( V - \frac{V^2}{aV_{\text{max}}} \right) \] \hspace{1cm} (5.18)
Similar to the speed-flow models which use the Greenshield's linear speed-density models, Equations 5.17 and 5.18 are expressions of the demands on the driver at various degrees of curve and speeds respectively. The equations seem to suggest a maximum demand occurring at some specific values, say, \( D_0 \) and \( V_0 \) of degree of curve and speed respectively. These values happen to be \( D_{\text{max}}/2 \) and \( V_{\text{max}}/2 \) respectively for a linear model as given in Equation 5.16a. The maximum/critical value of demand for \( D_0 \) and \( V_0 \) is given by:

\[
\text{RID}_0 = \frac{V_0 D_0}{c}
\]

\[
\text{RID}_0 = \frac{V_{\text{max}} D_{\text{max}}}{4c}
\] \hspace{1cm} (5.19)

What happens in practice could be completely different, but what Equations 5.17 and 5.18 show is that, speed management strategies may be geared towards some optimum driver workload value. This optimum/maximum value can however occur, or be exceeded at other values of \( D \) (road complexity) when driver speed management strategy fails. Failure may occur by way of higher speeds adopted, possibly as a result of inconsistent design, or other violation of driver expectancy.

Equations 5.17 and 5.18 are the equations of positive guidance as given by Alexander and Lunenfeld (1985). Since the idealized driver is driving with the intention of keeping rate of information processing demand below a certain critical level \( \text{RID}_0 \) (shown in the combined plots in Figure 5.4), design can be tuned so that this level of \( \text{RID}_0 \) is not exceed
with any combination of road complexity (eg. degree of curve $D$) and operating speed. Consistent design controls complexity so that the driver reacts in such way that $\text{RID}_0$ is not exceeded.

![Diagram](image)

Figure 5.4: Graphical representation of the relationship amongst curvature, speed and $\text{RID}$.

Equations 5.17, 5.18 and Figure 5.4 are a simplified representation of the demand placed on the driver with the assumption that the only source of demand on the driver whilst tracking a curved section is that due to the curvature. In which case, when the degree of curve is equal to zero on a straight road section, the demand on the driver is zero. Theoretically, the driver can drive at infinite speed or to the limitations of the vehicle under this condition. This is evident from the latest land speed record of approximately
1,223 km/hr, which was set in the Nevada desert in 1997 (ThrustSSC, 2003). When driving on the road however, roadway width restrictions and restrictions on the general layout of the road mean that demand is not zero at zero curvature even when one assumes that there is no other road user on the road. The parameters of Figure 5.4 are thus best determined in an experiment in which driver workload is measured independently.
CHAPTER 6
DRIVER WORKLOAD EXPERIMENT

6.1 PURPOSE OF EXPERIMENT

The use of the workload concept in system design aims at designing so that the capabilities of the operator are not exceeded at all times. This requires a quantitative knowledge about the relationship between system attributes and operator workload, as well as the tolerable workload limits of the operator.

Knowledge about the factors affecting driver workload is well established, but as stated in the foregoing sections, researchers have found it difficult to incorporate all the factors in the assessment of driver workload. This is apparently an inherent problem in the general workload research, and it is brought about as a result of the multi-faceted nature of the workload construct. It is generally accepted that the determinants of operator workload are centered on three factors which come under: task complexity, time available to complete a task, and the operator’s psychological/physiological state. An additional factor in the workload literature is the operator’s adaptive capabilities.

In driving, the time available to perceive and process information is determined by the speed at which the driver traverses the road. The workload experienced by the driver should therefore be a function of the factors of road complexity, operating speed, driver state, and strategies which the driver might employ to manage workload. Driving has long been described as a self-paced task, and the self-paced nature is mainly as the result
of the driver's ability to manage the experienced workload by direct intervention. This
direct intervention is at all levels of the driving task; from strategic level (choice of route,
journey time, and mode of transport), manoeuvring level (speed management), but the
latter is where experienced workload is determined. By way of adaptive strategy, the
driver is able to stay below the overload level when driving motives require that higher
speeds be adopted. The driver can also choose speeds so that workload is maintained at a
comfortable level. So, by incorporating driving strategies in driver workload modeling, it
is possible to investigate critical levels of workload for geometric design as well as the
design of in-vehicle information systems.

This experiment investigated the relationship between workload and the measurable
factors of road complexity and speed in the first part, and the effects of driver adaptive
strategies (at the manoeuvring level) on the experienced workload in the second part.

6.2 EXPERIMENTAL DESIGN

This section describes the experimental set up in terms of the variables
(independent/controlled, dependent) and the type of experiment. From the purpose of the
experiment, it was desired to know the effects of road complexity and driving speed on
the workload which the driver experiences. It was also required to know how the driving
strategy affects experienced workload in real life.

Complexity of the road mostly comes from the design features of the road as well as
traffic on the road. This experiment investigates the effects of curvature on driver
workload with the belief that findings could be extended to other road features such as lane width, lane drops, bridges, intersections, etc.

6.2.1 Experimental Variables

The controlled variables in the first part of the experiment were curvature and driving speed. By making the subjects drive an experimental track which consists of curves of various radii; subjects were exposed to varying road complexities at different speeds. Table 6.1 shows the planned levels of the two variables with an ‘x’ marking the feasible combinations with respect to safety and practicality.

Table 6.1: Variables to be tested

<table>
<thead>
<tr>
<th>Radius (m)</th>
<th>30</th>
<th>50</th>
<th>65</th>
<th>80</th>
<th>100</th>
<th>Leisure Driver</th>
<th>Late Driver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tangent</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>200</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>160</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>100</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>60</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Assuming that familiarity with the road environment also affected driver workload, driver familiarity was investigated by separating results of the first time a driver traverses the track from subsequent runs. The response variable for this first part of the experiment was driver workload; measured in terms of the attention demanded at the various radii and speed combinations. A pocket computer, placed on the dashboard of the experimental vehicle, generated numbers at the rate of 2 numbers per second. Subjects first repeated the random numbers (secondary task) whilst the vehicle was standing still. The score at this stage was considered to be the 100 percent score of the driver; equivalent to the
subject's capacity. Then while the vehicle is in motion on the experimental track, subjects were directed to pay full attention to the driving task, and used any spare capacity to repeat the random numbers. The difference in percentage terms between the score whilst the vehicle was stationary and the score whilst in motion gave the subjects attention demand at the level of road complexity and speed.

The second part of the experiment investigated the driving strategy adopted by drivers as their driving behaviour is affected by their motives. A driver who is in a hurry would adopt a different strategy compared to one who is just having a leisure drive. Driving strategy was investigated by letting subjects drive whilst mimicking two driving scenarios; namely the leisure driver, and the late driver. The leisure driving scenario was representative of a driver on a Sunday afternoon leisure drive and the participants were instructed thus, and to drive at their comfortable speeds. The late driving scenario was representative of a driver who is late for an important interview. The late driver would therefore drive at their maximum safe speed. The response variable in this case is the speed which the driver will adopt at various sections of the track in order to control the workload experienced. These scenarios were tested for each radius as shown in Table 6.1.

6.2.2 Test Track

The test was carried out at the Boundary Bay Airport testing site in Delta, BC; a facility used by the Royal Canadian Mounted Police (RCMP) and Justice Institute (JI) of British Columbia to conduct driving tests. It is a disused runway having dimensions of 60m width and approximately 1.2km in length.
Figure 6.1: Layout of Experimental Track
The restrictions of the dimensions of the site placed limitations on the radii of curves and length of track that could be set out on the runway. During the testing, only a limited part of the JI portion of the test facility was used because another test was being conducted on part of it.

In order to replicate the lane width on roads, the test track was set out with a width of 4m, and was delineated with 12 inch traffic cones. The track consisted of 10 segments with a test run starting on Segment 1, going through the numerical order sequence to segment 10, which joins segment 7 on the return leg of a run. Figure 6.1 shows the layout of the test track whilst Table 6.2 gives the geometric characteristics.

Table 6.2 Geometric characteristics of experimental track

<table>
<thead>
<tr>
<th>Segment #</th>
<th>Radius (m)</th>
<th>Deflection angle (Δ)</th>
<th>Tangent length (m)</th>
<th>Curve length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Tangent</td>
<td></td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>200</td>
<td>25</td>
<td></td>
<td>87.26</td>
</tr>
<tr>
<td>S3</td>
<td>Tangent</td>
<td></td>
<td></td>
<td>69.81</td>
</tr>
<tr>
<td>S4</td>
<td>160</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S5</td>
<td>Tangent</td>
<td></td>
<td>123</td>
<td></td>
</tr>
<tr>
<td>S6</td>
<td>100</td>
<td>45</td>
<td>78.54</td>
<td></td>
</tr>
<tr>
<td>S7</td>
<td>60</td>
<td>45</td>
<td>47.12</td>
<td></td>
</tr>
<tr>
<td>S8</td>
<td>Tangent</td>
<td></td>
<td></td>
<td>77.45</td>
</tr>
<tr>
<td>S9</td>
<td>26</td>
<td>246.71</td>
<td>107.2</td>
<td></td>
</tr>
<tr>
<td>S10</td>
<td>60</td>
<td>111.71</td>
<td>68.78</td>
<td></td>
</tr>
</tbody>
</table>

6.2.3 Test Runs

Given the speed scenarios in Table 6.1, and the need to obtain at least 3 data points for the unfamiliar as well as the familiar driver, the experimental design planned to test 21 drivers. This was to make it possible to assign 3 drivers to one speed scenario in order to
obtain the required data points for the unfamiliar driver for each speed scenario. A driver is considered to be unfamiliar for the first time he/she drives on the road. Data for all subsequent runs are for the familiar driver. The data requirement for the unfamiliar driver was the determining factor for the number of participants. The second and third runs were deemed to be adequately representative of the data requirement for the familiar driver. Each driver therefore ran the test track three times (3 runs, see Table 6.3), and in order to obtain a complete set of results for the 7 speed scenarios, it was designed to test seven drivers on each day of testing. The whole experiment was therefore planned to be executed in 3 days. Table 6.3 shows the arrangement for a particular day for 7 drivers. Each speed scenario is randomly assigned to the drivers in each run, and whether a particular speed scenario is tested 1st, 2nd, or 7th (test sequence) is also randomly assigned.

Table 6.3: Experimental Runs for Each Subject

<table>
<thead>
<tr>
<th>RUN</th>
<th>SPEED SCENARIOS (km/hr)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
<td>50</td>
<td>65</td>
<td>80</td>
</tr>
<tr>
<td>1</td>
<td>3,4</td>
<td>2,2</td>
<td>4,3</td>
<td>1,6</td>
</tr>
<tr>
<td>2</td>
<td>2,3</td>
<td>7,1</td>
<td>3,6</td>
<td>1,4</td>
</tr>
<tr>
<td>3</td>
<td>5,7</td>
<td>2,2</td>
<td>4,5</td>
<td>3,4</td>
</tr>
</tbody>
</table>

The numbers in bold type represent subject number and test sequence for each run respectively. For example; for the 1st run, the speed of 30km/hr will be done by Subject # 3 and this will be 4th in the time sequence.

6.2.4 Subjects

The subject composition covered both sexes drawn from many walks of life and age groups, who freely volunteered to participate in the experiment based on a request for volunteers sent to their e-mail addresses. The sample could therefore be described as a
self-selected sample. The main conditions for volunteering were: (1) at least 3 years of
driving experience, and (2) at least 5000km of driving per year. Although it was intended
to test 21 participants in 3 days of testing, the experiment ended up testing 24 participants
of whom 5 were female and 19 males. This sample size was based on the experimental
design described above. Half of the subjects were graduate students from different
Departments of the University of British Columbia, in Vancouver. Table 6.4 shows some
of the characteristics of the subjects.

Table 6.4: Details of subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age Distribution</th>
<th>Sex</th>
<th>Years of Driving</th>
<th>KM Driven per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>21-30</td>
<td>M</td>
<td>14</td>
<td>8,000</td>
</tr>
<tr>
<td>2</td>
<td>31-40</td>
<td>M</td>
<td>30</td>
<td>2000</td>
</tr>
<tr>
<td>3</td>
<td>x</td>
<td>F</td>
<td>8</td>
<td>10,000</td>
</tr>
<tr>
<td>4</td>
<td>x</td>
<td>F</td>
<td>23</td>
<td>30,000</td>
</tr>
<tr>
<td>5</td>
<td>x</td>
<td>M</td>
<td>26</td>
<td>15,000</td>
</tr>
<tr>
<td>6</td>
<td>x</td>
<td>M</td>
<td>10</td>
<td>1,000</td>
</tr>
<tr>
<td>Day2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>x</td>
<td>M</td>
<td>10</td>
<td>15,000</td>
</tr>
<tr>
<td>2</td>
<td>x</td>
<td>M</td>
<td>5</td>
<td>25,000</td>
</tr>
<tr>
<td>3</td>
<td>x</td>
<td>M</td>
<td>12</td>
<td>15,000</td>
</tr>
<tr>
<td>4</td>
<td>x</td>
<td>M</td>
<td>5</td>
<td>25,000</td>
</tr>
<tr>
<td>5</td>
<td>x</td>
<td>M</td>
<td>32</td>
<td>20,000</td>
</tr>
<tr>
<td>6</td>
<td>x</td>
<td>M</td>
<td>52</td>
<td>10,000</td>
</tr>
<tr>
<td>7</td>
<td>x</td>
<td>M</td>
<td>15</td>
<td>20,000</td>
</tr>
<tr>
<td>8</td>
<td>x</td>
<td>F</td>
<td>36</td>
<td>18,000</td>
</tr>
<tr>
<td>9</td>
<td>x</td>
<td>M</td>
<td>36</td>
<td>50,000</td>
</tr>
<tr>
<td>Day3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>x</td>
<td>M</td>
<td>15</td>
<td>500</td>
</tr>
<tr>
<td>2</td>
<td>x</td>
<td>M</td>
<td>12</td>
<td>10,000</td>
</tr>
<tr>
<td>3</td>
<td>x</td>
<td>M</td>
<td>10</td>
<td>20,000</td>
</tr>
<tr>
<td>4</td>
<td>x</td>
<td>M</td>
<td>39</td>
<td>25,000</td>
</tr>
<tr>
<td>5</td>
<td>x</td>
<td>M</td>
<td>45</td>
<td>30,000</td>
</tr>
<tr>
<td>6</td>
<td>x</td>
<td>M</td>
<td>7</td>
<td>8,000</td>
</tr>
<tr>
<td>7</td>
<td>x</td>
<td>F</td>
<td>30</td>
<td>30,000</td>
</tr>
</tbody>
</table>
On the average the male participants were aged between 31 – 40 years, with 22 years of driving and 16 km of driving per year. The female participants on the other hand were in the 41 – 50 years age group, with 27 years of driving and 13,500 km of driving per year on the average.

6.2.5 Equipment

The vehicle used in the experiment was a Ford Focus SE 4 door sedan model, owned by the RCMP. A mini compact pocket PC used for the random number generation was placed on the dash board in front of the driver as shown in Photo 6.1. The numbers generated and the times at which they were generated were stored in a computer.

![Photo 6.1: Interior of Experimental Vehicle showing random number generator and tape recorder. Delineating cones on the test track are seen through the windshield.](image)
The position of the vehicle in terms of global coordinates, and its speed were captured every second by a GPS system. This information and the times at which it was captured were downloaded to a laptop computer placed in the trunk of the car. A g-analyst installed in the car measured longitudinal and lateral accelerations at intervals of a 10<sup>th</sup> of second. This information was downloaded to another computer, also placed in the trunk of the car. As a backup to the measurements, a Datron optical reader suspended between the two back wheels of the car measured the yaw rate, speed, lateral and longitudinal accelerations of the vehicle (also at intervals of a 10<sup>th</sup> of a second). The data was also downloaded unto another computer in the trunk of the car. The three computers were synchronized to start recording data simultaneously. The verbal record of the random numbers by the participants was stored on a tape recorder placed on the dashboard of the vehicle.

Photo 6.2: Trunk of Experimental vehicle showing data storage computers and Datron optical reader
6.2.6 Driver Attention Demand

Driving or tracking a course demands the attention of the driver. Since driver information is 90% visual, estimating the visual demand of the driver whilst driving on roads of different complexities should give an indication of the information contents associated with the complexities. As a result, visual demand gives an indication of driver workload. Specialized equipment is normally used to occlude the vision of drivers when measuring visual demand. This according to McDonald et al. (1975), blocks the fovea as well as the peripheral vision. A secondary visual task which leaves peripheral vision untouched is more representative of what happens in driving.

The secondary task chosen in this experiment was random number repetition. It is based on the theory of limited human information processing capacity. When the road is demanding more of the driver's attention, less capacity will be available to attend to the secondary task. The pocket PC used for the purpose of the random number generation is equivalent to any in-vehicle information device in use today. They all require the attention of the driver away from the road.

To estimate driver attention capacity, drivers repeated the random numbers generated from the pocket PC whilst the vehicle was stationary (both before and after each run). The percentage of numbers repeated was calculated to give the 100% score of the driver. This was compared with the percentage of numbers repeated whilst the driver drove the various sections of the track in order to estimate the attention demands on the various sections as follows:
Let the percentage of numbers repeated when the vehicle is stationary be \( C \%), and for a particular speed/complexity combination on the track, let the percentage of numbers repeated by the driver be \( X \% \).

The attention demand (AD) for this scenario is calculated as follows:

\[
AD = \frac{C - X}{C} \quad (6.1)
\]

For \( X = 0 \), \( AD = 100\% \) and for \( X = C \), \( AD = 0\% \)

### 6.3 PROCEDURE

A complete factorial experiment investigating the various levels of the two factors of road complexity (radius) and speed scenarios would have satisfied the requirements of this experiment. Safety and practical considerations, however, meant that only a limited combination of factors could be tested. Also, time and administrative constraints did not permit a complete randomization of the runs as indicated in Table 6.3.

Table 6.3 required randomization of the speed allocation to subjects as well as sequence of runs for Runs 1, 2 & 3. For example, after the allocation of a speed scenario to a driver for a Run set (Run 1, for instance), the sequence of run (that is, whether this driver would be the 1\textsuperscript{st}, 2\textsuperscript{nd}, etc, or 7\textsuperscript{th} to do his/her speed scenarios) would have been determined randomly. This would have provided a completely randomized experimental procedure to take care of the time effects. Complete randomization would, however, have required the downloading of information from the three computers 21 times (3 runs * 7 subjects) and resetting subject information the same number of times. This procedure was considered to be very time consuming, and the risk of mixing up data for the subjects as each one of
them is handled 3 times during the day was very high. Another problem was that the subjects did not arrive at the site at the same time to assign them randomly to sequences. So, depending on the subjects’ time of arrival at the site, they were randomly allocated speed scenarios in Runs 1, 2 and 3, and each subject completed his/her 3 runs consecutively before another subject was considered. Each subject was therefore handled only once during the experiment.

Cruise control would have served very well in the investigation of the various speed scenarios. It would have reduced the requirement on the driver to maintain speeds at the various levels; a situation that is bound to induce its own demands on the driver. In the absence of cruise control, and the need to reduce the attention required to maintain speed, subjects drove the car from the site office to the start point of the test on Section 1 (see Figure 6.1) whilst practicing the speed in the next run.

Before testing, each subject was given a form in which they entered information about their age, driving experience and number of kilometres driven per year on the average. The purpose of the experiment was then explained to the driver. They were told about the secondary task (number repetition), and told to consider driving the car along the test track at the designated speed scenario as their primary task. In that case, they were told to concentrate all their attention on maintaining performance on the primary task (driving the car along the track), and to use any spare time left to attend to the secondary task. A drawing of the test track was then shown to the subject and the course to be taken
explained. The fact that there were mostly one set of cones to be followed along the track was also explained to the subject.

Having received this initial information, the subject was taken to the test vehicle and requested to sit in a comfortable driving position by adjusting the seat. At the start of the experiment, the subject was asked to repeat as many of the numbers being generated from the random number generating pocket computer in front of them as possible whilst the vehicle was stationary, and the response was recorded on the tape recorder provided on the dash board of the vehicle. The subject was then told to drive to the start of the track (Chainage 0, Section 1) whilst practicing the immediate speed scenario.

At the start of the track, the importance of the primary task was again stressed to the subject before giving the go ahead to drive at the speed scenario. The experimenter watched the speedometer and informed the subject when the target speed was reached so that the subject can maintain that speed. The subject was then requested to repeat as many numbers as possible whilst maintaining the primary task of driving. The run was completed once the subject is back at the start of the track, where she/he is given the next speed scenario instructions.

At the end of the runs (at least 3, and sometimes 4), the subject drove to the main office where, for the second time she/he was requested to repeat the random numbers again whilst the vehicle was stationary. The response was once more recorded on the tape
recorder. Information from all the computers pertaining to a particular subject was then downloaded to a main storage computer under the subject’s name.

6.4 EXPERIMENTAL RESULTS AND OBSERVATIONS

As a result of concern for safety, accuracy in the experimental results, and time constraints, full randomization was not possible during the experiment as planned. The experiment was planned on a two factorial design to collect systematic data on stipulated levels of speed and road complexity (radius). Whist this was possible in terms of radius of curves, it was not possible to follow strict levels of the planned speeds. To do this in the absence of cruise control would have placed extra processing demand on the subjects. This means that the analysis for this kind of experiment, that is, a two-way factorial analysis was difficult to attain. To get data for systematic analysis of the effect of speed on driver attention demand, the speed data was approximated to the nearest 5km/hr for all the subjects. This however means that if a subject does not record 50km/hr; say for a particular radius, then data for other subjects who recorded 50km/hr for the particular radius cannot be compared in any meaningful statistical analysis.

6.4.1 Errors

A few sources of error were identified during the experiment. The most important were:

(1) those associated with faulty recording of random numbers resulting into missing data,

(2) those associated with synchronisation of the computers used for data recording, and

(3) those associated with workload due to speed maintenance. These are discussed in detail below together with the steps taken to alleviate the impacts.
1. Errors associated with faulty recording of random numbers: On listening to the tapes, breaks in recording due to mechanical failure of the microphone were noted on some of the tapes. The breaks were of two types: one connected to the stationary tests and the other connected to the runs. Breaks during the stationary tests were of a more serious nature since they determined the final scores for the rest of the experiment. Data for four (4) participants was disregarded as a result of serious breaks in the recordings for both stationary tests of random number repetition. Results were also disregarded for areas during the runs on the track where breaks were noticed. With an average of 4 seconds spent on most of the sections during high speed runs, a break during which 1 recording was missing out of the 8 numbers generated meant an error of 12.5% in the results. This required throwing out any data suspected of having breaks.

2. Errors associated with synchronisation of data storage computers: Errors in timing between the computers could have had a profound effect on the results. The three computers in the trunk of the car were synchronized to start recording at the same time. The clock on the random number generating computer needed to be linked with the clocks of the three computers in the trunk of the car so that random numbers generated could be linked with the correct positions of the vehicle on the track. With subjects spending on the average 4 seconds on sections during the fast runs, data out of place by a few seconds could be significant. A careful scrutiny of the recordings was required in order to avoid these errors.
From the coordinates of the Global Position System (GPS), the path of each run was plotted as shown in Figure 6.2. Each point on this chart corresponds to the speed at which the vehicle was running and the time when the vehicle was at the location. This time was tied in to the time on the random number recordings on the tape recorder and the random number generator to give an accurate representation of the location at which the recordings were made. Other random checks on the data were: (1) when the GPS started recording speed as this should be earlier than any random number repetition; and (2) other verbal outputs of the subject regarding direction or difficulty of the track.

Figure 6.2: A sample plot of coordinates for a run

3. Errors associated with the demand on driver to maintain speed: When drivers are required to run at particular speeds, it is possible that some driver attention is directed to the speedometer now and then in order to drive at the stipulated speed. This no doubt will
have its load on drivers in conjunction with the driving task loads so that the random numbers recorded may not be attributed to the task of driving alone. To reduce this error, drivers were told about their target speeds and made to practice it in some cases whilst going to the starting point. At the start of the experiment, drivers accelerated without looking at the speedometer. When they reached the target speed, the experimenter told them to maintain the speed at that point, and they were only asked to repeat the random numbers when the speed was steady around the target speed. The concern for driver workload due to speed maintenance was so high that the experimental design had to be relaxed. The use of cruise control could have avoided this relaxation in the experimental design.

6.4.2 Variation of Attention Demand with Curvature

Figures 6.3 to 6.8 show the effect of curvature (in terms of 1/Radius) on the attention demand of the driver for various speeds. Attention demand as defined in Equation 6.1, is the proportion of the driver's attentional capacity utilised for tracking a particular section of the track. The trend in attention demand was as expected, that is, as the complexity of the road increases (reduction of radius); the road demands more attention from the driver. Beyond 75km/hr, the data available was not sufficient to make any deductions. This was as a result of driving dynamic safety reasons requiring that only lower speeds could be achieved on the smaller radius curves.
Figure 6.3: Relationship between Attention Demand and Inverse of Radius at 35km/hr

Figure 6.4: Relationship between Attention Demand and Inverse of Radius at 40km/hr
Figure 6.5: Relationship between Attention Demand and Inverse of Radius at 45km/hr

Figure 6.6: Relationship between Attention Demand and Inverse of Radius at 55km/hr
The above relationships between attention demand and the inverse of radius for the various speed scenarios are compared in Figure 6.9 for unfamiliar drivers. Similarly, the one for familiar drivers is given in Figure 6.10.
Figure 6.9: A comparison of the relationship between Attention Demand and Inverse of Radius for various speeds (Unfamiliar Driver)

Figure 6.10: A comparison of the relationship between Attention Demand and Inverse of Radius for various speeds (Familiar Driver)
6.4.3 Effect of Driver Familiarity of Attention Demand

The effect of driver familiarity on driver's attention demand was also as predicted. As Figures 6.3 to 6.8 show, the same road complexity and speed combination situation was demanding more of the attention of the unfamiliar driver than the familiar driver.

6.4.4 Variation of Attention Demand with Speed

Variation of attention demand with driving speed is already evident from Figures 6.9 and 6.10. As the speed increased for a particular road complexity situation, the attention demanded of the driver also increased. Although Figures 6.9 and 6.10 show this trend, they are, however, limited in the coverage of the speeds encountered during the experiment. A clearer representation of the relationships between attention demand and speed for a particular road complexity are shown Figures 6.11 to Figure 6.14. These cover the relationship for a tangent section and the 200m radius curve for the unfamiliar driver as well as for the familiar driver.

![TANGENT SECTION (Unfamiliar Driver)](attachment:image)

Figure 6.11: Relationship between Attention Demand and Speed Unfamiliar Drivers on a Tangent Section
Figure 6.12: Relationship between Attention Demand and Speed for Familiar Drivers on a Tangent Section

Figure 6.13: Relationship between Attention Demand and Speed for Unfamiliar Drivers on a 200m Radius Curve
Figure 6.14: Relationship between Attention Demand and Speed for Familiar Drivers on a 200m Radius Curve.

The rest of the relationships between attention demand and operating speed for other road complexity situations (curvatures) are compared in Figure 6.15. Attention demand increases as road complexity and speed increase.

Figure 6.15: A Comparison of the relationship between Attention Demand and Speed for various Curvatures (familiar Drivers).
6.4.5 Speed – Curvature Relationships

To investigate the driver speed choice for the driving scenarios of the Late Driver and the Leisure Driver, the average speeds during these runs were plotted against the inverse of radius used as shown in Figure 6.16. Included in Figure 6.16 for comparison is the curve for the relationship derived from speed/curvature studies in Canada by Morrall & Talarico (1994). All the curves in Figure 6.16 follow those by Lamm et al. (1997) in Figure 5.3

Figure 6.16: Speed – Curvature Relationships for the 85th Percentile Driver

Regression analysis of the relationships in Figure 6.16 are as follows:

For the Late Driver,

\[ V_{85} = 94.858 - 1180.1 \times \left( \frac{1}{\text{Radius}} \right) \]

\[ R^2 = 0.88 \] \hspace{1cm} (6.2)

and for the Leisure Driver

\[ V_{85} = 56.833 - 510.27 \times \left( \frac{1}{\text{Radius}} \right) \]

\[ R^2 = 0.93 \] \hspace{1cm} (6.3)

Equations 6.2 and 6.3 are in the same form as Equation 5.16 which is
\[ V85 = A - b \times D \]

where \( A \) = maximum free speed, \( D \) = degree of curve, and \( b \) = constant

### 6.4.6 Effect of Driver Speed Adaptation on the Experienced Attention Demand

The relationships in Figures 6.3 to 6.15 should be adequate for the determination of the attention demand of driving as long as the levels of road complexity and driving speed are known. This should serve the purpose of estimating the workload of the operator, but it fails to help the designer to design proactively. Proactive design requires that the designer should know the limits to which the driver should be loaded so that design can be tailored in a way that will not exceed limits. Knowing this limit is important for all designs. The limiting situations in driving proposed by this research are: those of the leisure driver, the 85\(^{th}\) percentile operating speed driver, and the late driver.

Since the driver is assumed to be driving to keep workload within manageable limits and it is also assumed that speed is used to manage workload, then the workloads which the driver is experiencing during these limiting situations should be regarded as reasonable information processing limits of the driver. The assumption is that if the driver could process information at a higher rate, then speeds higher than those selected would have been chosen especially in the case of the late driver.

The foregoing Figures 6.3 to 6.15 already show the level of workload that the driver experiences at a particular level of road complexity for various speeds. Since the workload limits are set by driver speed choice, these limits can be established by
superimposing the speed/complexity (curvature) relationships that were observed during
the experiment on the charts which show the workload/curvature relationships for various
speeds. The superposition is accomplished as follows:

Considering the speed/curvature relationship of the Leisure driver shown on Figure 6.16
and also in Equation 6.3 (which was derived from the field data in Table 6.5), the self
imposed speed limits at the various curvatures should correspond to the workload limits
for leisure driving. For instance, the driver chooses a speed of 56.83km/hr on a tangent
section (zero curvature). So, on either of the charts in Figure 6.9 and 6.10, a location can
be found corresponding to this speed and curvature.

Table 6.5: 85th Percentile Driver Speed Behaviour for various Driving Scenarios

<table>
<thead>
<tr>
<th>Radius (m)</th>
<th>1/Radius</th>
<th>SPEED (km/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Leisure Driver</td>
<td>Late Driver</td>
</tr>
<tr>
<td>Tangent</td>
<td>0</td>
<td>56.83</td>
</tr>
<tr>
<td>400</td>
<td>0.0025</td>
<td>55.56</td>
</tr>
<tr>
<td>200</td>
<td>0.005</td>
<td>54.28</td>
</tr>
<tr>
<td>160</td>
<td>0.00625</td>
<td>53.64</td>
</tr>
<tr>
<td>100</td>
<td>0.01</td>
<td>51.73</td>
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<td>60</td>
<td>0.0166667</td>
<td>48.33</td>
</tr>
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<td>26</td>
<td>0.0384615</td>
<td>37.21</td>
</tr>
<tr>
<td>33.16</td>
<td>0.030157</td>
<td>41.45</td>
</tr>
<tr>
<td>50</td>
<td>0.02</td>
<td>46.63</td>
</tr>
<tr>
<td>28.44</td>
<td>0.035165</td>
<td>38.89</td>
</tr>
</tbody>
</table>

Figure 6.17 shows the results of the superposition of the driver speed models in Table 6.1
on a chart similar to Figure 6.10 but with a more diverse speed coverage. The curves in
Figure 6.17 were fitted to quadratic models as follows:

For the Late Driver scenario,

\[ \text{Attention Demand} = 31.501 + 3851.5D - 82671D^2 \]

\[ R^2 = 0.96 \] \hspace{1cm} (6.4)
Figure 6.17: The effects of Driver Speed Adaptation on the Attention Demand of Driving
For the 85th Percentile Road Driver as modeled by Morrall & Taralico (1992)

\[
\text{Attention Demand} = 34.858 + 1346.1D - 41365D^2 \\
R^2 = 0.8681...(6.5)
\]

and for the Leisure Driver

\[
\text{Attention Demand} = 23.962 + 1167.8D - 19933D^2 \\
R^2 = 0.98...(6.6)
\]

Where \( D \) is the inverse of radius \((1/\text{Radius})\), a measure of the degree of the curve.

The corresponding variations in driver attention demand with speed as speed adaptation takes place are shown in Figures 6.18 to 6.20 for the three speed behaviour models. This is to say that as drivers choose the speed behaviours (Table 6.5 or Figure 6.16), they are also choosing corresponding workloads as shown in Figures 6.18 to 6.20.

![AD-Speed Relationship for 85th Percentile Road Driver](image)

Figure 6.18: The effect of Driver's Adaptive speed behaviour on Attention Demand for 85th Percentile Driver on the road
AD-Speed Relationship for Late Driver

\[ y = -0.0611x^2 + 8.153x - 197.54 \]

\[ R^2 = 0.9348 \]

![Graph of AD-Speed Relationship for Late Driver](image1)

Figure 6.19: The effect of Driver’s Adaptive speed behaviour on Attention Demand for 85th Percentile Late Driver on the Experimental Track

AD-Speed Relationship for Leisure Driver

\[ y = -0.1523x^2 + 13.347x - 248.15 \]

\[ R^2 = 0.8716 \]

![Graph of AD-Speed Relationship for Leisure Driver](image2)

Figure 6.20: The effect of Driver’s Adaptive speed behaviour on Attention Demand for 85th Percentile Leisure Driver on the Experimental Track
A more direct representation of the above self-imposition of limits by the driver was shown when the raw data was plotted separately against the inverse of radius, and operating speeds. It was assumed that since the driver cannot exceed the limits whatever the driving scenario, then the upper bound (or envelope) of such plots should represent the capacity situation of drivers, which is exhibited by the late driving scenario as these drivers are driving to the limit. These plots are shown in the following Figures A.1 to A.12 in APPENDIX A. This time, the modeling of the speed behaviour of the unfamiliar driver (which was not possible using the superposition of the speed equations) was accomplished. It was also possible to differentiate between driver behaviours for the outbound and return journeys. Except for some outlier data points, the upper bounds (or envelope) of the data points tend to follow the curvilinear relationships of the form already experienced in Figures 6.17 to 6.20. In particular, there seems to be agreement between the charts shown in Figures 6.17 to 6.20 and envelopes which define the upper bounds of the data points in Figures A.1 to A.12 for the familiar driver. In the relevant charts, the maximum attention demand for the familiar driver happens to be just under 80% in both sets of charts.

To get equations similar to Equations 6.4 to 6.6, the data points on the periphery of cluster of points (upper bound or envelope) in Figures A.9 to A.12 (which combine the raw data for the outbound and return runs for the unfamiliar and familiar drivers) were modeled in a regression analysis. The resulting equations of the analysis and curves are shown in Figures 6.21 to 6.24. Again, the shapes of the resulting curves and the forms of the regression equations are similar to those produced in Figures 6.17 to 6.20. This means
that different speed behaviours can be superimposed on Figure 6.17 to give credible driving limits.

![Graph](image)

Figure 6.21: Data points for the relationship between attention demand and inverse of radius as affected by driving strategies of the unfamiliar Driver

![Graph](image)

Figure 6.22: Data points for the relationship between attention demand and inverse of radius as affected by driving strategies of the familiar Driver
Figure 6.23: Data points for the relationship between attention demand and speed as affected by driving strategies of the unfamiliar Driver

Figure 6.24: Data points for the relationship between attention demand and speed as affected by driving strategies of the familiar Driver
The curves and expressions in Figures 6.21 and 6.22 tend to exaggerate the maximum values of the attention demand. The sharper representations in Figures 6.23 and 6.24 however give a clearer view.

In Figure 6.23, the maximum attention demand of 65% occurs at around 55km/hr for the unfamiliar driver. The familiar driver's maximum of 80% occurs at about 65km/hr and (Figure 6.24). The expression for this maximum point for the late driver in Figure 6.19 tends to be shifted to about 65km/hr; however, the points used to model the relationship show a maximum at 60km/hr. Figures 6.3 to 6.8 show that for the same level of speed and curvature, the unfamiliar driver has a higher attention demand than the familiar driver. However a more cautious speed management strategy of the unfamiliar driver (if it works) more than compensates for this so that in the final analysis the workload experienced by the unfamiliar driver is lower (compare Figures 6.23 and 6.24).

For both the familiar and unfamiliar drivers, the maximum attention demand tends to occur at a 1/Radius value of 0.025m⁻¹ (40m radius). Substituting this value of the inverse of radius into the speed/curvature relationship for the late driver given in Equation 6.2, an operating speed (V85) of 65km/hr results. This is exactly what pertains in Figure 6.19; but then, Figure 6.19 was derived from Equation 6.2.

From Figures 6.21 and 6.22, it is evident that the attention demand increases steadily from the respective values at 1/Radius value of zero, to the maximum value. From then onwards the variation in attention demand is only slight with respect to increase in
1/Radius values, to the extent that it is true to state that the driver is trying to maintain control of attention demand so that it does not exceed a certain limit. The aim of the driver is not to attain a conscious target value of attention demand. The conscious aspect of driving is to reach the destination within the constraints of time, as stated for the late driver, but not at the expense of information processing capabilities of the driver. The decrease in attention demand after the maximum value could be an indication of cautious driving as road complexity increases, thereby increasing the workload margin. Workload margin here is defined as the difference between the 100% attention demand and the experienced attention demand.

According to the results, the 85th percentile driver on the road leaves a workload margin of about 50% compared to only 20% by the late driver. The leisure driver exhibits a more cautious attitude to speed with speeds ranging from just above 35km/hr to just above 55km/hr and a safety margin of 55% with respect to attention demanded.

6.5 THEORY VERSUS EXPERIMENTAL OUTCOME

Compared to the theoretical development, as indicated in Figure 5.4 (Chapter 5), the results in Figures 6.17 to Figure 6.24 appear to show some agreement. Accepting the fundamental theory of limited (constant) information processing capacity, the expressions for Rate of Information Demand (RID) in Equations 5.17 and 5.18 should equate to the Attention Demand (AD) measured in the experiment. The difference between the theoretical expressions of Equations 5.17 and 5.18, and the experimental outcome in Figures 6.17 to 6.24 is that theory assumed that curvature was the sole contributor to road
complexity. In that case, for a curvature of zero, RID equals to zero. In practice however, even lane tracking, which confines the driver within the lane markings requires some attention demand on the part of the driver. Out on the open highway, roadside restrictions, availability of adequate shoulders, and embankment slopes are some of the restrictions on the driver. These additional sources of complexity would affect driver speed behaviour as well as the driver attention demand and, as long as they are present, attention demand cannot be zero when curvature is zero. A slight reformulation of the theory is required.

There is actually no reason why Equation 5.16 should not remain in the simplified form that it was reduced to. The above revelation of practice seems to suggest that although a large portion of the variation of the $85^{th}$ percentile speed can be explained by curvature, (and the effect of curvature is more profound on accident causation), a theoretical formulation of the driver's experienced workload cannot be made without a consideration of the effect of the general road layout. Accordingly, the $85^{th}$ percentile speed can be accounted for by an expression including lane width, shoulder width, horizontal curvature, vertical curvature, and traffic volume as given in Equation 5.11 (page 104) which is generalized here in Equation 6.7.

$$V_{85} = A - b*D + c*LW + d*SW + e*AADT \quad (6.7)$$

where

$D$ = degree of curve
$LW$ = lane width
$SW$ = shoulder width
AADT = average annual daily traffic, and
A, b, c, d, and e are constants

For a particular road or road segment, most of these parameters are constant, and can therefore be grouped into a general constant term 'a', which would account for the general road layout. In which case Equation 5.16a still remains in its original form reproduced here as Equation 6.7a, but this time with the equation parameters including an aspect for road layout.

\[ V_{85} = aV_{\text{max}} - bD \]  
\[ (6.7a) \]

where \( a = f(h, g) \), \( h \) = driver attitude (motivation, goals, skills, etc), and
\( g \) = complexities of the road layout

\( V_{\text{max}} \) = maximum 85th percentile speed (km/hr)
\( b = aV_{\text{max}}/D_{\text{max}} \)
\( D_{\text{max}} \) = maximum degree of curve (degree/km) beyond which \( V = 0 \)

Equation 5.15a for the rate of information processing demand \( \text{RID} \) then becomes,

\[ \text{RID} = (g + D) \times V/c \]  
\[ (6.8) \]

where \( D \) = degree of curve (deg./100m)

\( g \) = complexity due to general road layout normalized to deg./100m. These include roadway width, nearness to roadside obstructions, etc. The effects of these parameters on driver speed behaviour is the same as that for curvature, that is, speed reduces as they become more severe.
\( V = \) available speed or approach speed (km/hr), and
\( c = \) constant

In Equation 6.8 when curvature is zero, \( V \) is \( a \cdot V_{\text{max}} \), so that \( \text{RID} = g(a \cdot V_{\text{max}}) \). Equations 5.17 and 5.18 now take the respective forms given by,

\[
\text{RID} = A + aD - \beta D^2 \tag{6.9}
\]
\[
\text{RID} = B + \xi V - \Phi V^2 \tag{6.10}
\]

Where \( D = \) degree of curve (deg./100m)
\( V = 85^{th} \) percentile speed, and
\( A, B, \alpha, \beta, \xi, \) and \( \Phi \) are parameters of the equation as determined in Equations 6.4 to 6.6 and Figures 6.18 to 6.24.

The practical representation of the relationship between Attention Demand (or RID), operating speed and curvature now becomes as shown in Figure 6.25.

Figure 6.25: Practical representation of the relationship amongst curvature, speed and RID.
6.6 CONCLUSIONS

Driver speed behaviour has been given many explanations, the latest of which is the time management strategy to control workload. Earlier theories by Wilde (1982) and Summala & Natannen (1974, 1976) have explained it in terms of risk management.

Using the theory of workload management as the primary role of speed control strategy, the experiment described in this report has shown that operating speed has two major roles in the determination of the attention demand (workload) in driving. In the first place, it can be seen why some models have failed to measure workload accurately, as workload depends on the speed at which the driver traverses a section (in addition to the complexity of the road). Speed is also the driver's main tool of managing the amount of attention demand that the driver finally experiences.

The use of a human factors approach and the cognitive aspects of human behaviour as is seen in the workload concept have long been advocated in the design of systems which depend on the human for their proper functioning (Forbes, 1972). The road is such a system where failure is associated more with the driver than the other aspects of the system. System design requires that the designer has knowledge of system attributes that cause workload, as well as the limits to which the operator can be loaded. The workload requirement is becoming even more important with the proliferation of in-vehicle information systems. The analysis of the effects of these systems on road safety can best be determined using a theory of driver attention demand. As the road demands attention from the driver, so also do in-vehicle information systems. To design the appropriate
interfaces to support in-vehicle information systems, researchers need to know the
loading from the road as well as the limits to which the driver can be loaded. The
interface should then be able to compare the extent to which the driver is already loaded
from road design with the load which information systems want to present to the driver.

Some researchers (e.g., de Waard, 1996) have avoided any investigation of what is
termed (by Weirwille et al., 1993) as the workload redline and advocated for measures
which give an indication of the presence of workload. However, this approach is
inadequate if workload is to be used as a design tool. A measure of the tolerable
workload limit is required, and this research has shown that it can be determined by
modeling of driver speed behaviour.
CHAPTER 7
APPLICATION TO DESIGN

Highway safety design practice has come to realize that the key to safe design is the consideration of the driver beyond what the design standard manuals provide. Despite the fact that some design guidelines are adopting a more behavioural approach (e.g., the Transportation Association of Canada (TAC, 1994) now has a section on design consistency), Kanellaidis et al. (1997) argue that design guidelines still suffer from what they term as a "human factors deficit". With more than 90% of road mishaps attributable to factors associated with the driver, the general agreement now in the road safety community is that the road system should be built to conform to the characteristics and performance of the driver. The main area of concern for human factors used to be with regards to the way highway geometric design affects driver performance, but recent developments of in-vehicle devices also mean that driver performance could be affected.

The effects of highway geometric design on driver performance come by way of driver interaction with complex designs which overload the driver's information processing capacity, causing high driver workload. Related to design complexity are inconsistent design practices that have a direct link to the violation of driver expectancies, leading to high workloads.

The thrust of design therefore is to design so that driver workload does not exceed capacity. In the first place, this means that the designer should have a means of predicting
workload accurately. Also, the designer should be able to predict driver capabilities so that design can be adjusted to the limits of the driver. The road designer needs to know which combination of road design features to put together so that driver workload is not exceeded. This aspect of design can be termed off-line design. Further, the designer of in-vehicle information systems needs to know how a new product will affect driver workload. Because of the diversity of such products, it is possible that two or more such devices can present information to the driver at the same time so that the combined information load or the mere presence of more than one source of distraction in the vehicle might present safety problems. For this reason, a central coordinating interface is now advocated by some practitioners (Michon, 1993). Fundamental to the central coordinating interface are the **WORKLOAD ESTIMATOR** and the **SCHEDULER**. The **WORKLOAD ESTIMATOR** should first of all be able to estimate the workload the driver is experiencing from the driving task and also the workload due to various information devices. The **SCHEDULER** then prioritizes the different sources of information and decides which information is needed by the driver depending on the present driving situation. It compares the total information load (that from the road plus the one from the information devices) to the capacity of the driver which is inbuilt into the system and decides whether to give information now or to wait.

The above narration of the estimation and scheduling of workload for the design of adaptive interfaces or on-line design appears to be a novel idea which has been investigated for the past 10 years by various researchers (Michon, 1993; Hancock and Verwey, 1997; Verwey, 1993, 2000). The need for workload estimation for off-line
design has been around for even longer. The main obstacle is the development of a model which can be used to estimate workload accurately. Measurement techniques such as primary and secondary task performance measures, subjective measures and physiological measures can be used in conjunction with theory to develop and verify such a model. The process however needs to consider the various parameters that determine workload. Apart from parameters intrinsic to the driver, theory has shown that the workload experienced depends on the load intensity, time available for action and adaptive strategies of the operator. In driving, these parameters come down to road complexity (load intensity), driving speed (as it represents time available), and driver adaptation (as seen in the use of speed management). The literature has explained how other models or measurement techniques failed to register experienced workload because they did not consider all these parameters, especially speed, in the estimation. The experiment in this report showed how these parameters can be included in a model whose application to design is now illustrated.

7.1 APPLICATION TO GEOMETRIC DESIGN

To design the features of the road so that driver information processing capacity is not exceeded requires an estimate of the effect of the various workload determinants on the driver's experienced workload as different sections of the road are traversed. The estimated workload is then compared with the driver's limits to see whether the limits are not exceeded. Any mismatch between the driver's processing limits and the workload, as demanded by the road configuration, is corrected by reconfiguring the design parameters. This off-line design process has also been termed as 'static adaptation' by Hancock and
Verwey (1997) to differentiate it from dynamic adaptation as used in the design of interfaces for in-vehicle information systems. The restrictive definition of dynamic adaptation to the design for in-vehicle information systems is due to the fact that workload is changing with time when in-vehicle systems are considered.

Workload is however generally a dynamic phenomenon, and in the case of driving it can hardly be considered static, especially when speed and traffic are considered. For the workload caused by design configurations, these configurations may be static, but the phenomena causing experienced workload, such as speed and its use as an adaptive strategy, are in a dynamic relationship. The role of design is to adapt or reconfigure workload parameters so that driver capacity is respected. Since driving is a self-paced task in which the driver is also actively involved in adaptation, the role of the designer comes into play when the driver's self-adaptive system fails. The self-adaptive system determines the limits to which the driver can operate and the designer configures design so that the designed workload does not exceed the limits.

7.1.1 Self-Adaptive limits of driving

Figure 7.1 shows two curves which define two driving limits; the top one representing the driving limits set by the late driver in the experiment and the other derived from the speed behaviour of the 85th percentile driver on the road. Considering the case for the late driver, Figure 6.17 and Figures 6.21 to 6.24 show that driving limits can be produced with some degree of accuracy by superimposing driver speed behaviour on the chart showing the relationship between attention demand and curvature for various speeds.
Wooldridge et al (2000) measured driver visual demand in experiments on a test track, on-road, and in a simulator. The visual demands measured were highly comparable. The relationship between visual demand and the inverse of radius for the test track experiments and the on-road tests were close enough to conclude that the results of test track experiments could be used to predict workload on the road. As a result, the on-road speed behaviour of the 85\textsuperscript{th} percentile driver derived by Morrall and Taralico (1994) was also superimposed on the chart showing the attention demand/curvature relationships in the experiment reported in this thesis.

![AD-Curvature Relationships](attachment:figure7.1.png)

**Figure 7.1: Self-Adaptive driving limits**

Under normal circumstances, the curves in Figure 7.1 are the limits which the late driver and the 85\textsuperscript{th} percentile driver would normally set themselves for various radii of curvature. The late driver scenario might have pushed it a bit far to the physical limits of the
driving, which puts the driver in a continuous state of stress with very little workload margins. In normal driving however, the driver leaves herself/himself a level of workload margin that allows for unforeseen events which might arise on the road. The general road safety practice is to provide for the needs of the 85th percentile since it caters for a majority of drivers. This research provides for the workload of the 85th percentile driver in the same light. If the normal driver is driving so that workload does not exceed a certain level, then the workload limits of the normal 85th percentile driver should cover the requirements for a majority of drivers.

The limits in Figure 7.1 would tend to suggest that the driver follows an attention demand curve which states the limits at various levels of road complexity (curvature). The same argument should then follow when the limits are plotted against speed as shown in Figures 6.18 to 6.20. To understand the workload management strategy of the driver, a closer look at Figure 6.22 is needed. For this reason the data on the upper bound that was used to draw the curve are plotted in Figure 7.2 below. The attention demand tends to rise rapidly from the value of about 33% at zero curvature to the maximum value just below 80% at a 1/Radius value of 0.015m–1 (67m radius). From then on, the variation of attention demand is not that remarkable. One can therefore say that the processing limit, or rather the operational limit set by the late driver, which may include some operational margin, is given by the dashed line in Figure 7.2. From a 1/Radius value of zero to 0.015m–1, the driver is limited by the capability of the vehicle, fear of speed, or speed limits. Beyond 1/Radius value of 0.015m–1, the driver is limited by driving dynamics of safety as dictated by the lateral acceleration. Table 7.1 shows that the driver is operating
at the limiting speeds for the last two small radius curves. As a result of the high load intensity (high $1/R$ values) on the right hand side of Figure 7.2, the potential for reaching the limit is high, but speeds have to be reduced to limit the lateral acceleration, whereas for the left hand side, speeds are not high enough as a result speed limit regulations, or limitations of the vehicle.

Table 7.1: Speed Scenarios compared with the theoretical maximum

<table>
<thead>
<tr>
<th>Radius (m)</th>
<th>Speeds (km/hr)</th>
<th>V$\max$ (theoretical)</th>
<th>Late Driver</th>
<th>Leisure Driver</th>
<th>Morrall driver</th>
</tr>
</thead>
<tbody>
<tr>
<td>$200$</td>
<td>$142$</td>
<td>$88.96$</td>
<td>$54.28$</td>
<td>$80.89$</td>
<td>$54.28$</td>
</tr>
<tr>
<td>$160$</td>
<td>$127$</td>
<td>$87.48$</td>
<td>$53.64$</td>
<td>$77.57$</td>
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</tr>
<tr>
<td>$100$</td>
<td>$100$</td>
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<td>$48.33$</td>
</tr>
<tr>
<td>$26$</td>
<td>$50$</td>
<td>$49.49$</td>
<td>$37.21$</td>
<td>$26.31$</td>
<td>$37.21$</td>
</tr>
</tbody>
</table>

$V_{\max} = \sqrt{g \cdot f_{\max} \cdot R}$, $g = 9.81 \text{m/s}^2$ (acceleration due to gravity), $f_{\max} = 0.8$ (frictional factor)

The above analysis tends to suggest that the driver may have some spare capacity at some points of the driving which can be used to perform extra activities. This spare capacity is represented by the area between the dotted line and the data points in Figure 7.2. The same applies to the case of the 85th percentile driver as illustrated in Figure 7.1. The existence of spare capacity on the high curvature side is however misleading. Spare capacity exists in this region only as a result of overcautious speed behaviour in the
presence of high curvature, and it happens only when the driver’s speed management strategy is working. More often than not, this is the region where driver capacity is exceeded as result of inappropriate speeds caused by violation of driver expectancies. In which case, driver speed management strategy is said to have failed.

The operational limit of the 85th percentile driver is around 50% according to the results of this experiment. Between this value and the limits set by the 85th percentile curve, the driver has spare capacity (represented by the shaded area) within the operational limits which can be used to attend to additional activities.

![Figure 7.2: Raw Data Limits of the Late Driver](image)

Proposed general limitations on design according to Figure 7.1 are as follows:

Above the limits of the late driver = **OUT OF BOUNDS**,  
Between the limits of the late driver and the 85th percentile driver = **WARNING SIGN**  
Up the limits of the 85th percentile driver = **GOOD DESIGN**
The proposed limitations can be set up as road design criteria related to driver workload as shown in Table 7.

Table 7.2: General limits of Attention Demand (AD) for design

<table>
<thead>
<tr>
<th>SAFETY CRITERION</th>
<th>GOOD DESIGN AD ≤ 50</th>
<th>WARNING SIGN 50 &lt; AD ≤ 80</th>
<th>OUT OF BOUNDS AD &gt; 80</th>
</tr>
</thead>
</table>

7.1.2 Geometric Design Approach

The aim of design is to design so that the 'experienced workload' does not exceed that of a majority of drivers. The practice in other areas (e.g., design consistency) has been to design for the needs of the 85\textsuperscript{th} percentile driver. This, in other words, means to adapt design so that the self-adaptive workload limit of the 85\textsuperscript{th} percentile driver is not exceeded. But first of all, there is a need to know how the self-adaptive limit of the driver is exceeded.

From the self-paced nature of driving, one would expect that the driver would drive on the road as it is built in a way that would limit the workload to a manageable level. From the analysis of driver behaviour, this is exactly what the driver sets out to do, that is, to adapt speed so that workload is maintained within a manageable level. At least this is what the attention demand curves representing the workload behaviour of the late driver and the 85\textsuperscript{th} percentile driver seem to show. Ordinarily, the workload which the driver experiences is a combination of road design and the operating speed. The road, once built, will contain a certain amount of complexity per kilometre built into it. A driver can
choose to drive at some speed and accept more or less workload as the charts show in Figures 6.9, 6.10, or 6.15. Generally the driver's speed choice is affected by motives, but whilst on the road, the actual speeds adopted may also be affected by the expectations which upstream sections would provide. So, if upstream sections are providing for higher speeds, as represented by the 85th operating percentile speed, the impression is that this trend continues to downstream sections. However, if downstream sections require lower speeds for adequate information processing, then speed reductions are required in order to track these sections with spare capacity. So if speed reductions do not occur in time, the tendency is that the higher upstream speeds are carried on to the downstream sections. The implications for this are twofold: (1) information processing load increases, and (2) the danger for exceeding the driving dynamic vehicle safety limits increases.

The risk of exceeding dynamic vehicle safety limits of driving has been the subject of design for a long time and it is the basis of safety design in highway design standard manuals. But what the literature and this experiment have shown is that, the information processing capacity of the driver is also affected, that is, driver workload increases. Designing for workload is therefore very important especially in situations where the ability to process information correctly is the main determinant of safety. This happens at intersections, built up areas, heavy traffic, and narrow bridge sites.

Since higher upstream speeds are the most likely to cause excessive processing problems downstream (if adequate speed reduction does not occur in time), any design approach should be to assume the upstream speeds as the available speeds $V_a$ as defined in the
equations for time pressure in Chapter 5 (e.g., Equations 5.5 to 5.15). In that case, after designing using the normal highway design standard manuals, the 85th percentile speeds are estimated using operating speed models such as the Morall and Taralico (1994) model. Upstream speeds are then applied to each section and the attention demand (workload) estimated using the charts in Chapter 6. These are then compared with the limiting attention demand (workload) for the 85th percentile driver in Figure 7.1. If the 85th percentile limit is exceeded, the design is reconfigured until they are at least equal.

7.1.3 Design Example

The design example investigates the experimental track used in this thesis to see how it conforms to the design criterion for workload given in Table 7.2. The same track will be investigated with respect to the operating speed consistency criterion given in Table 5.3 to see how the criterion for workload compares with that for design consistency. The 85th percentile speeds are estimated using the Morall and Taralico (1994) model (Equation 7.1) with adjustments made where the tangent length is not long enough to be evaluated as an independent tangent.

\[ V_{85} = \text{Exp}(4.561 - 0.0058 \times DC) \]  

where \( DC \), the degree of curve = \( 5729.58/R \) (deg./100m) and \( R \) = radius of curve (m)

Appendix B shows the evaluation of the test track (Figure 6.1) for the operating speed consistency criterion and the attention demand criterion developed in this report (see summary in Table 7.3). The evaluation covered both outbound and return legs of a run on
the track. The results are shown graphically in Figures 7.3 and 7.4 for attention demand and design consistency respectively.

Figure 7.3: Evaluation of Test Track for Attention Demand criterion

Figure 7.4: Evaluation of Test Track for Operating Speed Consistency Criterion
Table 7.3: A summary of evaluation of the test track for Operating Speed Consistency Criterion and Attention Demand Criterion

<table>
<thead>
<tr>
<th>Segment #</th>
<th>Radius (m)</th>
<th>Deflection angle (°)</th>
<th>Tangent length (m)</th>
<th>Curve length (m)</th>
<th>Degree of curve</th>
<th>Operating Speed consistency Criterion</th>
<th>Attention Demand Criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Tangent</td>
<td></td>
<td>150.00</td>
<td>0.00</td>
<td>-</td>
<td>ok</td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>200.00</td>
<td>25.00</td>
<td>87.26</td>
<td>28.65</td>
<td>Fair Design</td>
<td>Warning</td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>Tangent</td>
<td>38.50</td>
<td></td>
<td>0.00</td>
<td>-</td>
<td>ok</td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td>160.00</td>
<td>25.00</td>
<td>69.81</td>
<td>35.81</td>
<td>Fair Design</td>
<td>Warning</td>
<td></td>
</tr>
<tr>
<td>S5</td>
<td>Tangent</td>
<td></td>
<td>123.00</td>
<td>0.00</td>
<td>-</td>
<td>ok</td>
<td></td>
</tr>
<tr>
<td>S6</td>
<td>100.00</td>
<td>45.00</td>
<td>78.54</td>
<td>57.30</td>
<td>Poor Design</td>
<td>Warning</td>
<td></td>
</tr>
<tr>
<td>S7</td>
<td>60.00</td>
<td>45.00</td>
<td>47.12</td>
<td>95.49</td>
<td>Fair Design</td>
<td>Warning</td>
<td></td>
</tr>
<tr>
<td>S8</td>
<td>Tangent</td>
<td>77.45</td>
<td></td>
<td>0.00</td>
<td>-</td>
<td>ok</td>
<td></td>
</tr>
<tr>
<td>S9</td>
<td>26.00</td>
<td>246.71</td>
<td>107.20</td>
<td>220.37</td>
<td>Poor Design</td>
<td>Warning</td>
<td></td>
</tr>
<tr>
<td>S10</td>
<td>60.00</td>
<td>111.71</td>
<td>68.78</td>
<td>95.49</td>
<td>-</td>
<td>ok</td>
<td></td>
</tr>
<tr>
<td>S7</td>
<td>60.00</td>
<td>45.00</td>
<td>47.12</td>
<td>95.49</td>
<td>-</td>
<td>ok</td>
<td></td>
</tr>
<tr>
<td>S6</td>
<td>100.00</td>
<td>45.00</td>
<td>78.54</td>
<td>57.30</td>
<td>-</td>
<td>ok</td>
<td></td>
</tr>
<tr>
<td>S5</td>
<td>Tangent</td>
<td>123.00</td>
<td></td>
<td>0.00</td>
<td>-</td>
<td>ok</td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td>160.00</td>
<td>25.00</td>
<td>69.81</td>
<td>35.81</td>
<td>Fair Design</td>
<td>Warning</td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>Tangent</td>
<td>38.50</td>
<td></td>
<td>0.00</td>
<td>-</td>
<td>ok</td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>200.00</td>
<td>25.00</td>
<td>87.26</td>
<td>28.65</td>
<td>Fair Design</td>
<td>Warning</td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>Tangent</td>
<td>150.00</td>
<td></td>
<td>0.00</td>
<td>-</td>
<td>ok</td>
<td></td>
</tr>
</tbody>
</table>

The design consistency criterion identified 2 curve sites (Segments S6 & S9) as being poorly designed and 5 curve sites (Segments S2, S4 & S7 on the outbound journey, and Segments S4 & S2 in the opposite direction) in the fair design category. All the sites identified by the design consistency criterion as either poor or fair designs were identified for warning in the attention demand criteria. The 2 poorly designed sites (S6 & S9) identified by the design consistency criteria could however pose very serious workload problems to an unfamiliar driver whose self-adapted driving limits are much lower. From
Figure A.9 (Appendix A), the unfamiliar driver has a limit of about 65% attention demand. These two sites pose attention demands of about 62% (Figure 7.3). For the design of rural principal and minor arterials where the proportion of unfamiliar drivers is high, one would suggest that these 2 curve sites require a redesign to reduce the attention demand. Even for the familiar driver, the attention demand for these two sites is far more than those of the others, for which a warning was suggested by the evaluation criterion. One can therefore conclude that the results of the evaluation by the two criteria are comparable. The advantage of the workload criteria is that its use may be extended to cover many road situations including the evaluation of in-vehicle information systems.

7.1.4 Implications for Driver Underload

Design for the 85th percentile driver according to Figure 7.1 means that there are some situations where the driver experiences underload. Except for transient conditions of underload, prolonged underload situations can deactivate the driver leading to reduced driver attention that is not adequate for emergencies that may arise now and then during driving. When the risk models talk about compensation during favourable conditions, prolonged underload situations may be the times when the driver may need to increase speed, or attend to other tasks in order to reduce boredom. As explained under Section 7.1.1, the existence of spare capacity in the high curvature regions should be treated with caution and not to be considered as underload situations. The driver is consciously trying to lower workload in this region with speed reduction and spare capacity exists only as a result of over cautious speed adaptation. When speed adaptation fails, inappropriately high speeds may combine with the high curvature to overload the driver. However, this is
not the case for low curvature locations which require speeds in excess of ordinary operating speeds to counter boredom. For prolonged driving under such a low stimulus situation, the driver is bound to be deactivated leading to safety-related problems. This may be related in part to the high proportion of fatigue/sleep related accidents on monotonous motorways than on other roads reported in the UK (Horne and Reyner, 1995). Lamm et al (1999) also cited reports about high crash levels on monotonous roads in Germany as far back in 1943. De Waard (1996) theorises that, because of the effort required to stay alert in the deactivating circumstances that monotonous situations cause, operators may actually be experiencing high workloads due to the reduced capacities.

7.2 APPLICATION TO THE DESIGN OF IN-VEHICLE INFORMATION SYSTEMS

The effective utilization of in-vehicle information systems has long been linked to the development of a central coordinating interface. This estimates workload from the road, as well as from the various sources of information (Michon, 1993; Hancock et al., 1997; Verwey, 2000), and then schedules the information both spatially and temporally so that driver workload is not exceeded. The main obstacle to this has been the lack of proper methods for the estimation of workload coming from the primary task of driving as well as from the information systems. After workload is estimated, the need still exists to determine the extent to which the driver can be loaded when all the sources of workload (road complexity and information sources) are put together. This might suggest the so-called workload “red-line” (de Waard, 1996), but according to the results and analysis of the experiment reported in this thesis, the driver on the road could be aiming at some
workload level less than the red-line value that might be associated with that of a late driver.

Armed with a means of estimating the workload due to road design and an idea of the loading limits of the driver; driver interface design becomes a bit more interesting. Interface design used to be limited to establishing whether there is extra processing capacity to accommodate the information before it is scheduled. If there is limited spare capacity, the information is postponed until spare processing capacity is available. This need not be the case, especially if the role of operating speed as a major contributor to experienced workload as well as its use as an adaptive tool is accepted. For information that is crucial, especially to safety, the driver can instead be instructed to reduce speed in order to accommodate crucial information. The future interface can be designed to be more of a CARING INTERFACE type rather than just a regulator. The modalities for the operation of such an interface are explained in Appendix C.

7.3 SUMMARY

Designing for driver workload has been of increasing interest to highway safety practitioners as the sophistication of the highway system increases. This interest has grown as a result of more complex road designs and the proliferation of in-vehicle information systems. The sole purpose of many in-vehicle information systems is to improve the operations of the highway system and safety, but they also introduced further safety concerns. Design for driver workload should now satisfy two areas as follows:
1. Off-line design which deals with the design for workload that is caused mainly by the way the design features of the road are designed, and

2. On-line design which deals with designing for the workload that the growing numbers of in-vehicle information systems might cause.

Paramount to both designs, and fundamental to any engineering design, is knowledge about what you are designing for in terms of supply and demand parameters. On the demand side, the road safety practitioner needs to estimate the levels of workload as the driver traverses a certain segment of road. On the supply side, the level of workload which the driver can take needs to be determined. The limiting workload value could of course be taken as that value of workload that corresponds to zero crashes, since failure of the highway system could be defined in terms of crash occurrence. The main problem with this approach is that it does not support proactive design.

To date, the highway safety community is still searching for credible methods of estimating workload both from the demand side and the supply side. Using methods of workload estimation developed from the experimental programme carried out in this research, the test track was evaluated off-line on the basis of workload requirements as well as operating speed consistency requirements. The areas identified by the design consistency criterion were also identified by the workload criterion, especially when the driving behaviour of the unfamiliar driver is considered. Figure 7.5 shows how the design can be completed in an iterative manner to arrive as a safe design.
The design process starts with design standard manuals, coupled with environmental and aesthetic concerns to produce an alignment design. The ensuing geometric design configuration and operating speed estimates can be used to estimate workload profile along the route. The workload values can then be compared with the workload design criteria for the 85th percentile driver and the late driver (familiar/unfamiliar) to see whether workload limits have been violated. The areas requiring redesign are identified.
and redesigned until the whole alignment is certified as conforming to the criteria for workload design.
CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

The need for accurate measurement and prediction of driver workload has grown over the years with the increase in sophistication of road design and the vehicles which drive on them. For normal design, otherwise known as off-line design, the engineer is interested in knowing which road design features or their configuration will overload the information processing capacity of the driver. Likewise, the designer of in-vehicle information systems also needs to know how the information devices affect the performance of the driver. This research particularly reviewed the problems associated with the measurement and prediction of driver workload. The conclusion is that the problems that plague the prediction of workload as reported in the general literature also exist in the field of driver workload prediction and assessment. These problems have been identified as follows:

1. Because of the multifaceted nature of the workload construct, most methods of measurement or prediction do not consider all the different facets in the formulation methods of prediction.

2. Most of the workload prediction models are not so founded in theory to have the predictive power required for reliable use. The theoretical definition of a workload measure is that it should have a direct relevance to workload and its components. So if a coherent theory cannot be found to combine the different facets, then they cannot all be considered in a predictive model.
A review of the literature for the assessment of driver workload suggests that driver workload is affected by:

1. The psycho/physiological aspects of the driver as represented by driver state of fatigue, motivation, age, sex, drugs, etc.
2. Road complexity as represented by the effect of design on driver behaviour, and traffic.
3. The use of in-vehicle information systems.
4. The operating speed which is determined by driver's perception of the road according to driver expectation.
5. Driver adaptation which is determined by driver speed behaviour under different driving scenarios.

Despite the body of evidence existing on the contribution of the above to driver workload, very few models give a full consideration of the effect of speed in the determination of the workload experienced by the driver. Most models or measurement techniques of driver workload consider road complexity as the main determinant almost to the exclusion of the effect of speed. This has lead to measurement techniques not registering the appropriate workload levels where such levels existed. The literature shows that the speed chosen by a driver determines the level of workload that the driver will experience. Therefore, when properly modeled, driver speed choices should give an indication of the driver's target workloads levels, which should then give an insight into some design levels of workload.
This research proposed a model of driver workload which combines road complexity (load intensity) and driving speed in a time pressure (TP) definition of workload. The expression for TP was combined with a basic model of driver speed behaviour to give a relationship describing a workload management strategy of drivers. The basic idea behind the research was; if driver workload is dependent on speed, and that the driver has control over speed, then under normal circumstances, the driver will choose speeds so that experienced workload does not exceed driver workload limits.

The model was tested in a test track experiment to investigate the effects of road complexity in terms of curvature, driving speed, driver familiarity, and driver adaptive strategy (determined by mimicking a late driver and a leisure driver) on driver workload. Twenty four (24) drivers drove the test track consisting of various horizontal curve radii at speed ranging from 30km/hr to 100km/hr and speeds of late and leisure drivers. The workload experienced by the drivers was measured using a secondary task of random number repetition. The results showed that as the variables of road complexity (measured in terms of curvature or the inverse of radius) and speed increased, driver workload also increased. Also, under the same conditions of loading (from road complexity and operating speed), the unfamiliar driver experienced more workload than the familiar driver. However, this was offset by the more cautious speed management strategy adopted by the unfamiliar driver.

The modeling of driver workload management strategies seems to suggest that drivers aspire to some optimal level of workload, depending on the driving scenario. The results
of the experiment showed that when late, the unfamiliar driver aspires for an attention demand (workload) of 65% whilst the familiar driver’s aspired attention demand was 80%. The results also showed that when taking a leisurely drive, driver attention demand is fairly close to 45%. Modeling the speed behaviour of the 85th percentile driver on the road suggests that drivers aim at an attention demand of about 50%.

The above aspired attention demand levels however were not attainable in all road situations. In low road complexity situations, the speed is not high enough to attain the aspired attention demand. This could be as a result of limitations of the vehicle, speed limits and/or cautious driving. In high complexity situations, driver speed is controlled by driving dynamic safety considerations so that driver attention demand is low. The driver may therefore be assumed to have spare capacity (relative to the aspired attention demand) on some sections of the road.

A simple approach was used in this research to model driver speed behaviour, and the above therefore may not be the absolute values required for design. Indeed human behaviour is complex and no one can give absolute answers. But the results may be a step forward; towards highlighting the role of speed in the assessment of driver workload. The results suggest the following:

1. That drivers drive to a limit and that driving limits can be determined to some extent; these limits should determine workload levels for design purposes
2. That, whilst following these self-imposed limits (depending on the motives), there are some situations on the road where the driver has spare capacity. These spare capacity situations can be used for the design of in-vehicle information systems.

3. That, since driver workload depends on speed, the designer can use speed in both static (off-line) and dynamic (on-line) situations to control the workload that the driver experiences.

8.2 RECOMMENDATIONS AND FURTHER RESEARCH

8.2.1 Recommendations

The general literature of workload tends to be inundated with various methods of measurement, each with its own scale. Workload also happens to be mediated by the human operator, and because of the variability in human characteristics, the workload experienced by one individual may be different from that experienced by another. Because of this variability, practitioners (de Waard, 1996; Wooldridge et al, 2000) have recommended against the use of absolute measures of workload. Also, it was recommended that critical (or capacity) levels of workload or redline values should not be considered. These recommendations, however, mean that the theory of workload is left for academic exercise and cannot be used in design. Design requires some acceptable level of workload against which design may be compared.

The fact that there is variability in human behaviour and characteristics is accepted. Very few parameters in design are deterministic, and therefore they require a stochastic approach for analysis of design. The stochastic nature of perception reaction time
(another human characteristic) has not prevented its use in the design of stopping sight distance. It is therefore recommended that explicit consideration be given to workload estimation in the geometric design of roads.

The advantages for using the theory of driver workload in the design of the road system include the following:

1. The workload theory seems to provide a theoretical foundation for human factors practices of design consistency and safety audits, which have depended purely on empiricism and expert knowledge.

2. Workload analysis can cover a whole range of design features not covered by speed consistency evaluation.

3. Workload analysis is the only means by which the workload due to in-vehicle information systems can be assessed.

The design process as represented in highway design standard manuals has only a limited consideration of the characteristics of the driver in relation to driving dynamic safety. The driver’s contribution to mishaps on the road extends beyond what happens in driving dynamics. Perception and cognition errors also do occur as a result of high workloads so that finding a way of assessing workload complements the safety design process. A car on an icy road may easily fail as a result of traction failure whereas a car in a heavily
built up area may fail as a result of perception and cognition errors of the driver. The mechanisms of these two errors are not the same, suggesting that no one method of analysis can account for the two at the same time. Future analysis of the car-driver-roadway system would best represent what happens on the road by treating the system like any man machine system in which it is sometimes necessary to undertake system analysis by analysing machine and human reliability separately, and then combining the two reliabilities to develop a more robust safety design tool.

Navin (1990) and Navin et al. (1998) have already shown how reliability analysis could be used to account for driving dynamic safety. Their analysis estimated the probability of failure or rather; the probability of non-compliance of the road system mainly based on the demand and supply of longitudinal and lateral acceleration. This may be said to account for the machine aspect of the road system as it deals with the mechanics of vehicle movement on the road surface.

The human reliability aspect is, to a large extent covered by driver reaction to road design as represented by the workload theory. The probability of driver failure will then be related to the probability of exceeding the operational limits of the driver as given in Figure 7.1. It is recommended that the attention demand limits of the $85^{th}$ percentile driver be considered as good design practice, and any design more than the limit of the late unfamiliar driver be subject to further review and redesign. The road design community has used the characteristics of the $85^{th}$ percentile driver in many design calculations since this limit tends to account for a majority of drivers. Where there is
doubt with regards to the acceptance of the limits of either the 85\textsuperscript{th} percentile driver or that of the late unfamiliar driver, stochastic approach may be used as is normally the case in reliability analysis.

In the final analysis, the road system fails if either the machine aspect (driving dynamics) or the human aspect (workload), or both fail. Mathematically, the probability of system failure ($F_s$) may be given by:

$$F_s = F_m + F_h - F_m F_h$$

where $F_m$ = probability of machine failure (driving dynamics failure), and $F_h$ = probability of human failure (workload failure)

8.2.2 Further Research

To make the application of the workload theory more useful to highway design practice, further research is needed in the following areas:

1. More on-the-road experiments need to be conducted in order to bridge the gap between laboratory kind of experiments and the real road situation. What is needed most of the time is to evaluate the effects of road design on driver behaviour, requiring that such experimental investigations can be conducted on unopened highways.

2. Experimenting with other road design features, as well as a combination of features is necessary. Although curvature happens to account for most of the
variability associated with workload and its parameters, the experimental investigation showed that a predictive model has to account for some other aspects of the road, which this research put under one term as the road layout; the roadway width (carriageway and shoulder widths), nearness to roadside objects such as cuts, embankments and other artificial obstacles contribute to the road layout. Apart from the road layout, other road design features such as intersections, whether the road is 2 or 4 lanes, divided or undivided need to be considered.

3. The effect of traffic density on workload also needs to be investigated. A study by Verwey (2000) showed no relationship between workload and traffic density. Speed-density relationships give no explanation for the phenomenon, but the same kind of relationship exists between speed and information density (road complexity) on the road. This research shows that driver speed behaviour is directly related to the driver's desire to control workload. It is believed that driver speed behaviour in traffic may, to some extent, be related to the control of workload as traffic density increases. This needs to be investigated in order to account for the driver's total workload.

4. In order to assess the workload due to in-vehicle information systems, the workload due to these devices needs to be assessed. Experiments need to be conducted to determine the effects of these devices on driver workload at various speeds. Only then would one be sure of how they will fit into the assessment
process. Many guidelines already exist on the use of such systems. The guidelines are, however, restrictive in the sense that the workload associated with them still remains to be assessed. Most guidelines are in relation to the time taken to use the system whilst the vehicle is at rest. This definitely gives an indication of the workload involved, but a way should be found to combine this time measure with the workload experienced from the road whilst driving at various speeds. It is difficult to say whether the time needed to operate the system whilst the vehicle is at rest will be the same when in motion and at various speeds.
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APPENDIX A: PLOT OF RAW DATA ON ATTENTION DEMAND VS INVERSE OF RADIUS AND OPERATING SPEED

Figure A.1: Raw data for Attention Demand/Inverse of Radius Relationship for Unfamiliar Driver-Outbound

Figure A.2: Raw data for Attention Demand/Inverse of Radius Relationship for familiar Driver-Outbound
Figure A.3: Raw data for Attention Demand/Speed Relationship for Unfamiliar Driver-Outbound

Figure A.4: Raw data for Attention Demand/Speed Relationship for familiar Driver-Outbound
Figure A.5: Raw data for Attention Demand/Inverse of Radius Relationship for Unfamiliar Driver-Return

Figure A.6: Raw data for Attention Demand/Inverse of Radius Relationship for familiar Driver-Return
Figure A.7: Raw data for Attention Demand/Speed Relationship for Unfamiliar Driver-Return

Figure A.8: Raw data for Attention Demand/Speed Relationship for familiar Driver-Outbound
Figure A.9: Raw data for Attention Demand/Inverse of Radius Relationship for Unfamiliar Driver-Outbound & Return

Figure A.10: Raw data for Attention Demand/Inverse of Radius Relationship for familiar Driver-Outbound & Return
Figure A.11: Raw data for Attention Demand/Speed Relationship for Unfamiliar Driver-Outbound & Return

Figure A.12: Raw data for Attention Demand/Speed Relationship for familiar Driver-Outbound & Return
APPENDIX B: EVALUATION OF TEST TRACK FOR OPERATING SPEED CONSISTENCY AND ATTENTION

DEMAND CRITERIA

<table>
<thead>
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APPENDIX C: MODALITIES FOR THE OPERATION OF A MORE CARING DRIVR INTERFACE FOR IN-VEHICLE INFORMATION SYSTEMS

According to Figure C1 the driver interface is in communication with the road, the various in-vehicle information devices, the vehicle, and the driver. From the information on the road regarding design (whether in a sharp curve, built-up area, intersection) and the speed of the vehicle, the **ESTIMATOR** makes an estimate of the amount of attention (AD$_R$) the road is demanding from the driver. This is continuously being compared (by the **COMPARATOR**) with the processing limit (AD$_L$) of the driver to see whether there is any information processing mismatch in this first instance. If there is a mismatch, the **SCHEDULER** sends information to the driver, probably by audio, to adopt a speed (the required speed $V_r$ in Equation 5.6) appropriate for the complexity of the coming road.

Interface design is being employed in this case at points where off-line design fails to make the driver adopt speeds that respect the safe loading limits.

When information is available from the in-vehicle information devices, the **ESTIMATOR** prioritizes the information and calculates the attention demand (AD$_D$) from the device whose information is in line to be presented to the driver. The **COMPARATOR** adds the device attention demand to the road attention demand (AD$_R$) provided the latter is less than the driver’s limit in attention demand AD$_L$, to arrive at the total attention demand (AD$_T$). AD$_L$ and AD$_T$ are compared to see if there is any mismatch. If there is no mismatch, meaning that the total attention demanded is less than the driver’s limit, the information is presented to the driver. If there is any mismatch, the **SCHEDULAR** does not immediately postpone the information in case it is very
important for safety or operational purposes. If the driver is approaching a curve at a high speed that might cause rollover or skidding, this information cannot wait. Also if the driver is about to miss an exit that may cause serious operational problems (which sometimes leads to safety problems), the information cannot wait. Instead the driver is warned to reduce speed in order to accommodate the crucial information. This way, the interface is acting more like a caring device, that is, it is trying to keep the driver out of critical workload situations.
Figure C1: A Caring Adaptive Driver Interface