Development of a Knowledge-Based System for Heavy Vehicle Legality and Stability

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ABSTRACT

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A Knowledge-Based System, (KBS): VELSAS (VEhicle Legality, Stability And Sensitivity), is developed to study the legality (Weights and dimensions) of tractor-semitrailers operating in Québec, and to evaluate the roll stability and sensitivity of these vehicles for different sets of vehicle parameters. The laws and regulations controlling the use of these vehicles are studied and the system requirements defined. Expert systems are introduced and a survey of available expert system shells and tools is carried out. Two shells, EXSYS and VP-EXPERT are evaluated by building a prototype of the desired expert system and VP-EXPERT is chosen as the development tool. The system is built following a loop of prototyping, verification and validation. The final system determines the vehicle legality in three aspects: dimensions, axle loads and gross weight. If the semitrailer axle loads or gross weight is illegal, KBS: VELSAS suggests certain modifications to the vehicle in order to make it legal. The final system is evaluated and a few sample runs are provided. In order to study the vehicle's stability and sensitivity, VELSAS calls two external FORTRAN programs.

The first program, utilizes a vehicle stability model, SRM, to calculate the vehicle rollover threshold and roll angle, and the second program estimates the sensitivity of the vehicle rollover threshold and roll angle to small variation in design parameters using a mathematical sensitivity analysis approach. In order to develop the mathematical sensitivity analysis, the static roll model of a tractor semitrailer is used and the necessary equations are derived. The reason for choosing the mathematical approach in sensitivity analysis, is to avoid the repetitive running of SRM required in previous sensitivity analysis studies. The sensitivity analysis method is illustrated by performing calculations on a candidate vehicle and the results of the more sensitive parameters are presented. The results show that the mathematical sensitivity analysis method can be used as a quick estimate to predict the roll angle, lateral acceleration and rollover threshold within reasonable error.

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NOMENCLATURE

a_y	Lateral acceleration
$[A]$	Coefficient matrix in sensitivity equations
$[\bar{A}]$	Coefficient matrix in SRM equations
A_i	Dual tire spacing on axle i
$\left[\frac{\delta A}{\delta P_i}\right]$	Partial derivative of coefficient matrix with respect to parameter P_i
C_{FR}	Tractor frame coulomb friction
F_{ij}	Force due to the j^{th} suspension spring on axle i
FR_i	Force acting through the roll center in a direction parallel to the $\vec{j}_u$ axis
F_{yi}	Lateral force at the tire-road interface of axle i
F_{zij}	Vertical force at the tire-road interface of the j^{th} tire on axle i
h	height of the vehicle center of gravity above ground level
HR_i	Vertical distance of the roll center from the ground plane
H_{Ui}	Vertical distance of the center of gravity of the i^{th} unsprung mass from the ground plane
K_{ij}	Vertical stiffness of the j^{th} suspension spring on axle i
K_{FR}	Torsional stiffness of tractor frame
$KOVT_{ij}$	Roll resisting stiffness at the tire-road interface of the j^{th} tire on axle i

KT_{ij}	vertical stiffness of the j^{th} tire on axle i
KYT_{ij}	Lateral stiffness of the j^{th} tire on axle i
K_S	Torsional stiffness of the fifth wheel
M_{FR}	Roll moment transmitted through the frame
OVT_{ij}	Roll resisting moment at the tire-road interface of the j^{th} tire on axle i
R_i	Roll radius of the tires on axle i
S_i	Half the lateral distance between the spring suspension on axle i
T_i	Half the lateral distance between the inner tires on axle i
W_{Si}	Weight of the i^{th} sprung mass on axle i
W_{Ui}	Weight of the i^{th} unsprung mass on axle i
$WAXL_i$	Load on axle i
W_{FR}	Vertical shear force acting through the tractor frame
W_5	Vertical load on the fifth-wheel
$\left\{\Delta x\right\}$	Variables vector in sensitivity equations
$\left\{\overline{\Delta x}\right\}$	Response variables vector in SRM equations
$\left\{\frac{\delta(\Delta x)}{\delta P_i}\right\}$	Sensitivity vector of response variables to parameter P_i
y_i	Lateral displacement of the axle i due to lateral compliance of the tire
Z_{FRi}	Vertical distance between the torsional axis of the tractor frame and ground plane (m)

Z_{Ri} Vertical distance between the sprung mass center of gravity and the roll center of axle *i*

Z_{Ui} Vertical distance between the roll center and the center of gravity of the i^{th} axle

Z_{Si} Vertical distance between the fifth wheel and the center of gravity of the i^{th} sprung mass.

$\Delta\overline{Z}_{Ui}$ Change in vertical distance from the fifth wheel to the center of gravity of the i^{th} mass including initial spring deflection

ZT_i Vertical deflection in inner tires on axle i

ϕ_{Si} Roll angle of the i^{th} sprung mass

ϕ_{Ui} Roll angle of the i^{th} unsprung mass

CHAPTER 1

INTRODUCTION AND LITERATURE SURVEY

1.1 General

In previous years, much work was done to study the stability and performance of heavy vehicles, and in particular tractor-semitrailers. In a report prepared by UMTRI (University of Michigan Transportation Research Institute), it was shown that about 77% of all combination vehicles operating in Canada are tractor-semitrailers [1]. The extensive use of these vehicles, accompanied by an undesirably high rate of accidents, led to various studies and regulations aimed at controlling the use of these vehicles and reducing their accident rate.

In a truck safety report presented in 1986, it was shown that vehicle rollover is the number one cause of fatal accidents in heavy vehicles [2]. In 1980, a static roll model (SRM) was developed and a program was written to study and evaluate the roll stability of tractor-semitrailers under steady state turning maneuvers [3]. The program evaluates the static rollover threshold which is defined as the maximum level of acceleration in units of gravity, beyond which a vehicle in a steady turn will undergo rollover. Further studies show that this rollover threshold is dependant on certain vehicle weight and dimension variables. The effect of changing certain vehicle parameters on the roll stability is of particular concern to those involved in the trucking industry. Different studies were done to investigate the sensitivity of roll stability to certain weight and dimension changes [4,5,6,7]. These studies show that the rollover threshold is indeed sensitive to the change in certain parameters such as track width and center of gravity (C.G) height.

For economic reasons, the trucking industry would like to see an increase in the maximum allowable size and weight limits. This increase, however, may lead to a reduction in vehicle stability and safety and increases the road damage caused by these vehicles. For this reason, the use of such vehicles is controlled by a set of weight and dimension regulations published by each provincial government. In the province of Québec, most of these regulations are in the form of tables and charts. The regulations control various vehicle dimensions, tire loads, axle loads and overall gross weight. The process of checking the legality of a certain vehicle is, in most cases, quite lengthy and requires obtaining certain variable values such as axle and tire loads.

The nature of the regulations, suggests the usefulness of developing a Knowledge-Based System (KBS) to determine the legality of a vehicle and to suggest legal alternatives if the vehicle is found to be illegal. The integration of of this KBS with other programs that study the stability and sensitivity of a desired vehicle would provide a means to evaluate that vehicle in three aspects of interest, namely, legality, stability and sensitivity.

1.2 Literature Survey

The Québec Ministry of Transportation has published various laws and regulations that define legal configurations with regard to weight and size limits. A vehicle operating in the province must meet all of the set regulations. Failure to do so, results in an illegal vehicle. In May of 1991, an updated set of regulations was published to define a revised set of load and size limits [8]. The purpose of this revision was to eliminate or reduce the need for special permits for vehicles that do not meet all of the load or size regulations. Since these regulations are mostly in the form of law articles that are not easy to apply, the Ministry of Transportation published a guide that presents most of the regulation in the form of tables and charts [9]. The guide defines different vehicle combinations and axle configurations. For each possible combination there is a limit on the axle loads and overall vehicle load. Each of these two limits is to be calculated using different methods, and the lowest result used as the limiting value. The above two publications also give certain constraints on different vehicle dimensions such as height, width and length.

Much research was done in the field of vehicle roll stability. In [3], three progressively complex roll plane models were presented to study the rollover process and to gain a better understanding of the forces and parameters involved in determining the rollover threshold. The first model, a rigid block representation of the vehicle, shows the maximum net restoring moment to be WT and a rollover threshold of T/h, where W is the total weight of the vehicle, T is the half track width and h is the C.G height. From this basic model it is clear that the half track width and C.G height are key parameters in determining the rollover threshold. The second model, a single-axle representation takes into consideration the compliance of the suspensions and the axles. The weight W, now represents the combined weight of both the sprung and unsprung masses, at a new C.G height h. In this model, it is found that the new value of the maximum roll-resisting moment is $WT-Wh\phi_c$, where ϕ_c is the roll angle at which the tire first lifts off the ground. The corresponding rollover threshold in this case is $T/h-\phi_c$. The smaller the angle ϕ_c, the higher the net restoring moment and rollover threshold. This implies that the rollover threshold can be improved by increasing the roll stiffness of the vehicle. The third model, a full roll plane model for computing the rollover threshold, uses a three roll plane model with three composite axles to develop the equations that describe the static equilibrium of the vehicle in the roll plane. The model yields a set of fifteen equations with fifteen response variables to a roll angle input. The roll angle is incremented and the fifteen equations solved simultaneously to evaluate the response variables. The vehicle response to the roll input is constantly checked for tire lift-off. When both the trailer and tractor rear tires lift-off the ground, the vehicle is considered to have reached an unstable position and the maximum lateral acceleration value achieved to this point taken as the rollover threshold. This last model, referred to as the SRM, will be used in this thesis for a detailed sensitivity analysis.

Different studies were done to investigate the influence of changing certain parameter values on the rollover threshold. In [4], it was concluded that the tractor frame stiffness, tractor frame coulomb friction, fifth-wheel stiffness and fifth wheel lash, have no effect on the rollover threshold.

In [5], the effect of changing certain parameters on a vehicle rollover threshold is analyzed by taking into consideration the precision with which each parameter could be best determined at a roadside station. The most sensitive parameters were found to be the trailer sprung mass C.G. height, tractor rear axle spring spacing, trailer dual tire spacing, trailer track width and trailer sprung mass.

In [6], a similar study is presented on the same model. The purpose of the study was to identify model parameters that require accurate measurement. The parameters considered were the tractor frame torsional stiffness, coulomb friction of the tractor frame, equivalent trailer structure and-fifth wheel compliance, separation moment and fifth-wheel lash, tire stiffnesses, suspension data and basic dimensions such as track widths and C.G height of the sprung masses. Some parameters were found to have no effect on the model rollover threshold results. These are the tractor frame torsional stiffness, the coulomb friction, the tire overturning stiffnesses and fifth-wheel lash. Other parameters were found to be necessary for the model but can be accepted with an error of approximately 25%. These parameters are the tractor front suspension, equivalent trailer structure and fifth wheel compliance and tire lateral stiffness. The rest of the parameters were found to affect the accuracy of the model output and thus require careful measurement.

In [7], the implication of changing size and weight parameters on rollover accidents is discussed. The parameters studied include axle loads, gross vehicle weight, width and C.G height. A plot of accident data versus calculated rollover threshold at different C.G heights suggests that vehicles having a payload C.G height of 90 inches or more will experience rollover in a substantial part of their accident involvement. It was also shown that increasing the lateral tire and spring spacings adds considerably to the roll stability of heavy vehicles. To perform the sensitivity analysis studies mentioned above, the relevant parameter value was changed and the program (SRM) run in repeated manner with the new parameter set. In [10], a mathematical sensitivity analysis method is described and will be applied to the static roll model in order to perform a parametric sensitivity analysis without repetitive running of the SRM program.

Artificial intelligence (AI) is an area in computer science concerned with the emulation of human thinking. Expert systems have emerged as a branch of (AI) concerned with the representation of human expertise in a system that can perform a difficult task normally undertaken by an expert. One of the earliest applications of expert systems is DENDRAL which is an expert system developed in Stanford University in the 1960's. The purpose of this expert system is to determine molecular and atomic structures using mass spectrogram. MYCIN, an expert system developed in Stanford University in the early 1970's, is used to diagnose bacterial infections and recommend the necessary treatment. Around the same time, PROSPECTOR, a natural resource expert system that evaluates geographic sites for potential mineral deposits, was developed. This expert system was able to locate a molybdenum mine with an estimated worth of one million dollars. In the past few years much work was done in the area of expert systems. Applications of expert systems have included medicine, chemistry, engineering and computer design, weather forecasting and teaching. In the field of teaching, an expert system is developed as a personalized training tool of civil engineering students [11]. The development of several expert systems has been initiated in collaboration with different industries and universities in the areas of design and test of aerodynamic models of flight simulators, speech recognition, monitoring hydroelectric dams and weather forecasting, [12]. The development of any expert system involves getting familiar with the topic of interest, performing a feasibility study, defining the system requirements , knowledge elicitation as well as several stages of prototyping and system evaluation.

In [13], a brief outline of the different stages of expert system development is given and a more detailed study of knowledge elicitation methods is presented. The methods discussed are interview, protocol analysis, induction and repertory grid technique. In [14], a structured approach to expert system design is presented. The main approach followed by the author involves (1) the development of a specific pattern for the interaction of the domain expert, the knowledge engineer and the system in the knowledge acquisition phase; (2) the identification of design areas that could be developed as independent modules with predefined interfaces; and (3) the application of the design areas to the acquisition, reasoning and explanation subsystems. Of major concern in the development of expert system is the choice of the proper tool or language for a specific application with certain requirements. In [15], a survey and evaluation of different expert system tools for engineering application is presented. The paper discusses certain desirable characteristics in an expert system tool. These include forward and backward chaining rules, hypothetical reasoning or the ability to consider multiple solutions to a problem, object description, integration of the above features, as well as the ability to be embedded as part of a larger system and to interface with other languages. A robust development environment that includes features such as intelligent editors, multiple windows and tracing option are very desirable during the developmental stages. Hardware independence and uncertainty management are also desirable features in a development tool. In this paper, the author provides a survey of development tools and their features. Some of the tools surveyed are ART, KEE, OPS5, OPS5+, Personal Consultant Plus and NEXPERT.

1.3 Scope of Thesis

The purpose of this thesis is to develop a Knowledge-Based System VELSAS (VEhicle Legality Stability And Sensitivty) that will give information regarding the legality, stability and sensitivity of a tractor-semitrailer. To give the necessary advice regarding the legality of a certain vehicle, VELSAS must contain all the relevant laws and regulations as published by the Québec government. Special care must be taken to insure that all the relevant information is correctly represented in the system. To establish the legality of a certain vehicle, different size and weight variables must be checked. The rules used for checking these variables should follow the same methods defined in the laws and regulations. VELSAS should be able to explain the reasons for any conclusions it might reach. Upon the completion of its run, VELSAS system will inform the user as to the different aspects of the vehicle's legality.

In case a vehicle is determined to be illegal, the system should provide the user with certain changes that can be made to the vehicle in order to make it legal. In order to build VELSAS, different languages and tools that are available are evaluated and a choice is made. Once VELSAS is developed, it is validated and the results are presented.

After a satisfactory configuration has been reached, the user will be given the choice of studying the stability of the vehicle by running an external program that will be called by VELSAS. This program will provide the user with different response variables, mainly the rollover threshold and roll angle of the vehicle. The user will also be given the option to study the effect of changing one or more parameters on the vehicle's stability. Such sensitivity studies were previously done by changing a parameter value and rerunning the static roll model. In this thesis, a mathematical sensitivity analysis based on the stability model of the vehicle will be presented. The aim of the study is to come up with a mathematical model for the vehicle's sensitivity to parameter changes, in order to avoid rerunning the simulation program with each parameter change. The needed programs will be developed and the results compared with those obtained by rerunning the static roll model.

CHAPTER 2

OVERVIEW OF EXPERT SYSTEMS AND EXPERT SYSTEM SHELLS

2.1 Introduction to Expert Systems

For about thirty years, there has been a lot of work and research being done on expert systems. But what are expert systems? Definitions for expert systems have been given by many authors and developers. Some of these definitions are given below:

An expert system is a computer based system that uses knowledge, facts, and reasoning techniques to solve problems that normally require the abilities of human experts [16].

An expert system is a computing system capable of representing and reasoning about some knowledge-rich domain, such as internal medicine or geology, with a view to solving problems and giving advice [17].

A Knowledge-Based (expert) System (KBS) is a computer program that performs a task normally done by an expert or consultant and which, in so doing, use captured, heuristic knowledge [18].

These definitions vary but the important thing to note is the common points highlighted in all of them that differentiate expert systems from other computer programs.

Some of the characteristics of knowledge based systems or expert systems are given below [16]:

- The system is expected to perform at an expert's level of competence.
- The expertise in an expert system comes from the special knowledge it has acquired.
- There is no programming or specific flow for how the system uses the knowledge that is presented to it and contained in it.
- The expert system should be able to deal with uncertain information with an associated certainty factor.
- The expert system should be able to perform with incomplete data.

Some additional properties of expert systems are:

- Reasoning: An expert system should be able to reason about its knowledge in such a way to come up with a useful solution.
- Depth: An expert system should be concerned and deals with deep knowledge and narrow subjects that require thorough knowledge and details about a certain topic.
- Self knowledge: An expert system should be able to justify its solutions or conclusions and explain how it has arrived to such a conclusion.

An outline of common characteristics of expert system tasks in contrast to characteristics of conventional software, will shed more light as to the nature of expert systems [18].

Knowledge-Based Expert Systems:

. Representation and use of knowledge

. Separation of knowledge and control

. Inferential processing

. Manipulation of large knowledge bases

. Relaxation of uniqueness and completeness

. Run-time explanation is a (desirable) characteristic

. Orientation: Symbolic processing.

Conventional Programs:

. Representation and use of data

. Integration of knowledge and control

. Algorithmic processing

. Manipulation of large databases

. Programmer insures uniqueness and completeness

. Run-time explanation is impossible

. Orientation: Numerical processing.

TERMS USED IN EXPERT SYSTEMS:

What follows is the definition of terms commonly used when discussing expert systems , and will be used in the discussion of this work [16]:

Artificial Intelligence: The attempt of a computational model to duplicate or simulate the mental faculties of human beings that make them appear intelligent.

Knowledge: Getting hold of certain facts, conditions, or principles, with a familiarity gained through experience or specialized association with a certain field. It can also be looked at as the integration of a collection of facts and relationships.

Knowledge Engineering: Deals with the presentation of the knowledge in a form usable by the computer. It involves acquiring the knowledge and reducing it into a definitive set of rules, facts or relations called a knowledge base.

Knowledge-based systems: Computer programs that use knowledge and inference to perform a difficult task usually done by a human expert. These systems include the knowledge in the knowledge base and an inference engine or a control mechanism for utilizing the knowledge and acquiring data or knowledge that might be missing.

Knowledge Engineer: A knowledge engineer has the task of acquiring all relevant knowledge from the expert and presenting it in a form that can be incorporated in the knowledge base. For this purpose, the knowledge engineer must interview the expert(s), and gather and interpret the information needed. From this definition, it is clear that the knowledge engineer should preferably be acquainted with both fields, expert systems and the topic of interest.

Inference Engine: The portion of the expert system that reasons and uses the knowledge in the knowledge base and the available facts to come up with a conclusion. The inference engine also provides knowledge acquisition and explanation capabilities where needed.

Rules: Rules are a special form of knowledge representation in the form of "IF.... THEN....." clauses. Depending on the tool or shell used, the clause could have the additional "ELSE" part in it.

Expert System Shells: The term expert system shell can have a different meaning to different users. In all the definitions; however, a shell is understood to provide a ready to run system except for the actual knowledge that needs to be included. The shell provides the user interface and the interence engine needed to reason about the knowledge. In a shell, the knowledge representation scheme and inference engine mechanism is predefined and the programmer has little, if any, control over it.

Expert System tools: Expert System tools are similar to expert system shells, except that they offer the builder more choice and control over the knowledge representation and inference mechanism. Thus tools are considered to be more of an expert system development environment.

Knowledge Representation: The method in which the different forms of knowledge and their relationships is encoded and stored. Some of the different methods of knowledge representation are given below:

Rules: Rules are the most popular form of knowledge representation. They are in the general form of:

IF (condition)
THEN (action)
ELSE (action)

as mentioned before, the availability of the **ELSE** part of the rule is dependant on the shell, tool, or language features. The **IF** part of the rule is called the premise or antecedent part. The **THEN** part of the rule is called the conclusion or consequent part. The action in this part may include a variable assignment, in which case it is possible to assign a certain degree of confidence to that value. Depending on the development software used such a rule would look something like this:

```
RULE1
IF
axle-type = tandem AND
axle-spacing >= 2.4 AND
load-type = timber_no_snow
THEN
trailer_max_load = 20000 CNF 100
```

where **CNF** stands for the confidence factor. A confidence factor of 100 implies a hundred percent degree of confidence. The confidence factor may also be assigned to clauses in the "IF" part of the rule. For the purpose of the expert system at hand, a confidence factor of 100 is always used. This is because the laws and regulations are absolutely defined. In most software, the rules can combine more than one clause in the premise and conclusion by the use of AND and OR terms.

Frames: A frame is a group of slots that hold attributes of certain objects, Figure 2.1. For each of these slots there is a corresponding space which holds a certain value attached to that attribute. That space may also contain a procedure that holds a certain set of instructions such as changing the value attached to a certain attribute or instructions for retrieving a specific value for the attribute from a certain database. Frames can be linked together to provide a relationship called inheritance. If frame 1 contains a general category of a certain item such as axles, and frame 2 contains a specific type of axle such as a tridem, then frame 2 will inherit the knowledge and procedures in frame 1.

Semantic Networks: A semantic network is a graphical representation of relationships between different objects. The objects are represented by nodes and the relationships by arcs connecting the different objects. A simple example of a semantics network is given in Figure 2.2. The direction of the arrows on the arc is dependent on the direction of the relationship. For example, the node "Humans", has two arcs connected to it. One arc has an arrow to the node and the other arc has an arrow from the node. From the figure, it can be seen that, like frames, semantic networks provide inheritance relationships. In this specific example, the node "Family Members", will inherit all the attributes of the node "Humans". Semantic networks are particularly useful when the relationships between the objects in the expert system are complex.

First-order Logic: This method of knowledge representation is suitable for declarative types of knowledge. There are four different types of logic systems: propositional calculus, predicate calculus, first-order predicate calculus and Horn clause logic. Given a number of true statements, propositional calculus will try to determine whether a new

Chair	
Slots:	**Entries (values):**
Owner	Judi
Parts	seat, back, legs, arms
Number of legs	4
Number of arms	2
Color	brown
Style	rocking
Owner's address	If needed, get owner's address from database-1

Figure 2.1 An Example on Frames [16].

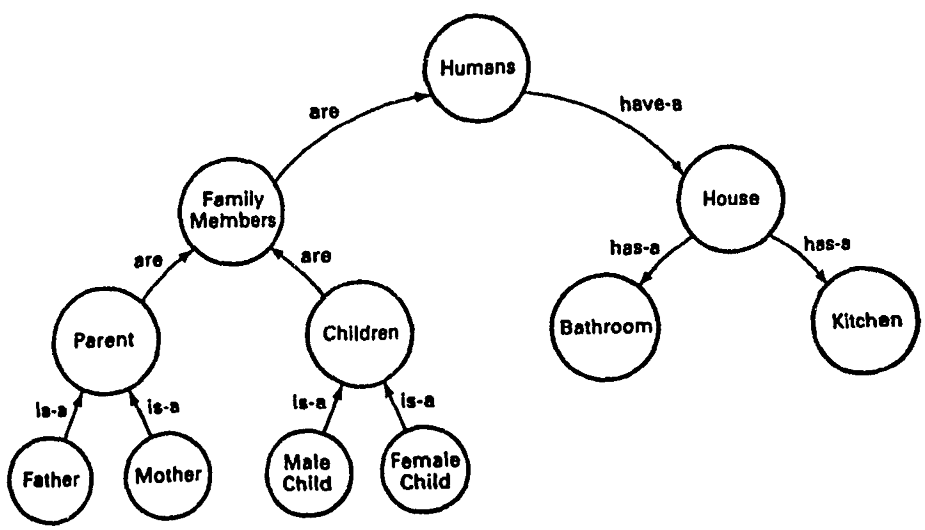


Figure 2.2 An Example on Semantic Networks [16].

statement or a proposition is true or false. In propositional logic, the relationships in the statements and proposition are limited to direct or simple relationships such as "is a" or "has a ". Predicate calculus is similar to propositional calculus in determining if the new proposition is true or false, but it also allows the use of more complex relations and generalized statements. The example given below will illustrate the difference between propositional logic and predicate logic:

If the following two statements are true:

. Lassie is a dog.

. If lassie is a dog, then she is a mammal.

Then given the following proposition:

. Lassie is a mammal.

the conclusion of the propositional logic will be that this statement is true.

In predicate logic, the first statement remains the same, whereas the second statement will contain a generalized statement:

. All dogs are bigger than all cats.

Then given the following proposition:

. Lassie is bigger than all cats.

predicate logic will conclude that this statement is true.

First-order predicate logic is an extension of predicate logic in which one may use functions such as "is-owned-by", or other analytical features. This type of logic system is popular in artificial intelligence.

Finally, Horn clause logic is a special form of first-order predicate logic that does not allow the use of negation or "not" relations. An example of a software that uses this form of logic is PROLOG, which is sometimes used in programming expert systems.

2.2 A Survey of Expert System Shells

From the previous section, it is obvious that the knowledge representation and inference mechanism plays an important part in the performance of an expert system. In [15], the author suggests certain desirable features in expert system tools.

The desired features include forward and backward chaining rules, hypothetical reasoning, object description, integration of features, integration with other languages, the ability to be embedded, high performance, a robust development environment, hardware independence, uncertainty management and the availability of knowledge acquisition aids. Table (2.1) provides a list of certain expert system tools and their capability level in each of these features.

TABLE 2.1: Some Expert System Tools and Their Associated Characteristics [15]

Expert System Tools

Tool	Forward Chaining	Backward Chaining	Hypothetical Reasoning	Object Description	Feature Integration	Language Integration	Embedded	Development Environment	Knowledge Acquisition	Uncertainty Managment	Base Language	Machines
ART	●	●	●	●	●	●	●	●			LISP C	LISP mach. VAX
KEE	◍	●	◍	●	●	●	●	●			LISP	LISP mach. VAX
Knowledge Craft	●	◍	◍	●	◍	●	?	●			Common LISP	VAX, PERQ LISP mach.
LOOPS	◍	◍	◍	●	●	●	?	●			Interlisp-D	Xerox 1100
S.1		●		●	●	●	?	●		●	LISP C	LISP mach. VAX
ESE (Prism)	◍	●			●	●	●	●		●	Pascal	IBM 370
TIMM	○			○	●			●	●	●	FORTRAN	many mach.
RuleMaster		◍			●	●	?	●	●	●	C	Vax, Sun Apollo
KES	◍	●	○	○	?			○		●	LISP, C	VAX, IBM PC Apollo
Personal Consultant	◍	●		◍	●	●		●		●	IQLISP	IBM PC
OPS5	●			○	●	○		○			LISP	VAX
OPS5+	●			○	●	◍	◍	◍			C	Macintosh IBM PC
CLIPS	●				●	●	●	◍			C	VAX IBM PC
M.1		●			NA	◍		◍		●	C	IBM PC
OPS83	●			○	●	●	●	?			?	VAX
Personal Consultant Plus	◍	●		●	●	●		●		●	Scheme	IBM PC
LES	◍	●		●	●	●		◍		●	PL/1, Ada	VAX
NEXPERT	◍	◍	○		NA	●	●	●			Assembly	Macintosh
BUILD	●	●		●	●	●	?	●			Prolog	SUN2

Capability Level: Full – ● Partial – ◍ Minimal – ○ None – Blank

As can be seen from this table, a strong presence in one feature for a certain tool is usually accompanied by a weak or absence of presence of another desirable feature. Thus it is not easy to find a tool that comprises all of the above features. In this case, the builder has to take a close look at the nature and requirements of the expert system to be built and make a decision based on this information.

What follows is a closer look at certain commercial expert system shells. Since one of the requirements of the expert system to be developed is that it has to be P.C. based, only P.C based shells will be looked at

2.2.1 INSIGHT 2+ [16]

INSIGHT 2+ DEVELOPMENT FEATURES:

INSIGHT 2+ is an expert system development shell that has two developmental languages and environments. The first is used to create the knowledge base using a language called Production Rule Language (PRL). The second, a combination of PASCAL and DBASE languages, called DBPAS can be used to generate or interact with external DBASE II and DBASE III databases and small Pascal programs. INSIGHT 2+ provides its own text editor used to develop PRL and DBPAS programs, as well as a database editor used to generate databases. The shell uses production rules for knowledge representation and features both forward (limited) and backward chaining. INSIGHT 2+ allows the chaining of knowledge bases that are able to share facts.

Through the use of DBPAS, INSIGHT 2+ can call external DBASE II and DBASE III databases. If the knowledge base requires certain data that can only be generated by standard programs, these can be developed in DBPAS and included as part of the expert system.

INSIGHT 2+ END USER FEATURES:

INSIGHT 2+ provides an explanation facility which allows the user to follow the line of reasoning used by the expert system. This feature is also useful in the developmental stages of the expert system. During a consultation, this facility provides the user with the means to examine and evaluate the responses given by the system.

2.2.2 PERSONAL CONSULTANT [16]

PERSONAL CONSULTANT DEVELOPMENT FEATURES:

PERSONAL CONSULTANT provides a simplified language based on LISP that can be used for entering rules into the knowledge base. PERSONAL CONSULTANT also allows the developer access to its underlying language LISP. This allows the experienced knowledge engineer to build a more tailored expert systems. In this sense, PERSONAL CONSULTANT can be considered to be more of a development tool than a shell.

PERSONAL CONSULTANT uses exhaustive backward chaining as its search strategy. The control structure is mainly determined by the order in which the antecedents (or IF part) appear in the rules. PERSONAL CONSULTANT cannot interface with external programs; however, it does allow LISP programming.

PERSONAL CONSULTANT END USER FEATURES:

PERSONAL CONSULTANT provides the user with a friendly window oriented user interface, explanation facilities and trace options which allow the user to follow the reasoning path that PERSONAL CONSULTANT took in a consultation. Customized user interfaces can also be developed in PERSONAL CONSULTANT because of the possibility of accessing the underlying language.

PERSONAL CONSULTANT PLUS

PERSONAL CONSULTANT PLUS is an enhanced version of PERSONAL CONSULTANT that offers faster execution, a larger knowledge base capacity and the use of graphics and other programs in PERSONAL CONSULTANT PLUS applications. PERSONAL CONSULTANT PLUS uses rule sets which are labeled as frames for its knowledge representation. Thus it is considered to be a frame based system. This is implemented by the use of three main knowledge structures: frames, parameters and rules. Frames are the global structure that represent general concepts and entities, and rules and the parameters are associated with these frames. In this representation, parameters are the means by which concepts or entities are represented in the frame. Each frame will automatically generate a set of parameters that are associated with it and parameters can be associated with more than one frame. Finally, rules represent the heuristics or reasoning and expertise on the expert system and are used to assign parameter values and communicate with the user. Just like parameters, PERSONAL CONSULTANT PLUS will automatically generate rule groups for each frame. Rules may be associated with more than one frame; however, one should insure that the corresponding parameters are also shared accordingly. The rules are in the form of (IF... THEN ...) statements. PERSONAL CONSULTANT PLUS offers both backward and forward chaining, but not simultaneously. The mode of chaining is by default backward, unless otherwise specified by a certain rule. Another point to make is that even though parameters can be inherited in frames, rules on the other hand cannot. Consequently, if a rule on one frame is needed in a subframe, it has to be explicitly associated with that subframe.

It is important to note here that both PERSONAL CONSULTANT and PERSONAL CONSULTANT PLUS are based on the

EMYCIN program which is mainly concerned with diagnostic type of problems. Thus the above two software were developed for and are mostly suited for building diagnostic and interpretation systems.

2.2.3 VP-EXPERT [19]

VP-EXPERT DEVELOPMENT FEATURES:

VP-EXPERT is a rule-based expert system development tool that stores its knowledge in the form of IF-THEN-ELSE rules. The information needed by the rules may be provided by one or more combinations of the following : user input, external programs called by VP-EXPERT, information base in database, work sheets and text files.

The knowledge base file in VP-EXPERT contains three basic elements:

- The ACTIONS block
- Rules
- Statements

a fourth element, clauses, are contained within the ACTIONS block and rules of the knowledge base.

The ACTIONS block

The actions block, defines the problems or goals of the consultation and the sequence of their solution. This is accomplished with FIND clauses that tell VP-EXPERT to find the value or values of one or more goal variables. In addition to the FIND clauses, the ACTIONS block can also contain other clauses that specify database operations, spread sheet operations or other tasks such as running external programs written in a different language.

Rules

Rules stated as IF/THEN/ELSE propositions, contain the actual knowledge or expertise of the knowledge base. A rule passes if all the conditions in its premise are satisfied. These conditions need not be simple one line conditions but could be the combination of two or more conditions connected by AND or OR. If the rule passes, then the conclusion will become true. The conclusion itself may result in the passing of another rule and so on. The conclusion may also result in the search for another goal that was not identified in the ACTIONS block. It should be noted here that the conclusion may be a multiple conclusion, in which case the conclusions are simply listed. Rules can occur in any order in a knowledge base, but, their sequence affects the path of the inference engine as it moves through the knowledge base. Consequently, execution speed can be affected by the rule order.

Statements

Statements contain information pertinent to the consultation itself. Most VP-EXPERT statements assign special characteristics to knowledge base variables. For example, the ASK statement identifies a variable whose value must be assigned by the user during the consultation process and poses the relevant question to the user. Another statement, the plural statement, identifies one or more variables as "plural", meaning that more than one value can be assigned to the variable(s) during a consultation. Other statements alter the execution of the consultation in some way. For example, the RUNTIME statement changes the appearance of the screen display during a consultation.

CLAUSES

Clauses always occur as part of the ACTIONS block or the conclusion of a rule. They are executed in the order of appearance in the ACTIONS block or a rule conclusion if the rule passes. The FIND clause was presented in the discussion of the ACTIONS block.

Now that the basic elements in VP-EXPERT have been presented, the highlights of the development features will be discussed.

- INDUCE COMMAND: One of VP-EXPERT's most powerful features is its ability to generate a rule base from an "induction table" by the use of the INDUCE command. The induction table, is a list of examples in the form of rows and columns. Upon the completion of the induction table, the induce command quickly generates a rule base that is a direct representation of the examples given in the induction table. This feature is limited in the complexity of the knowledge base it can create. However, in most cases it is very useful in the starting stages where a simple rule base is first created. The rule base may also be further completed by editing it into the desired complexity.

- BACKWARD AND FORWARD CHAINING: The problem solving or goal finding method used by VP-EXPERT inference engine is backward chaining. The inference engine starts by identifying the goal variable and then moves through the rules until it finds a value that can help it assign a value to the goal variable. This pattern continues until one of the variables sought has a known value. Once a value is known, the inference engine can retrace its steps and test the rules that provided its original path. Forward chaining is only used when the WHENEVER clause is activated. Backward chaining therefore is considered as the main goal finding method used.

- CALLING EXTERNAL PROGRAMS: VP-EXPERT can at any time call external programs through three different commands. BCALL executes a DOS batch file, then resumes the consultation. CALL executes a DOS EXE file, then resumes the consultation. CCALL executes a DOS or COM file, then resumes the consultation. In the last two cases, the command CLROFF allows for background processing of the programs.

- RECEIVING AND SENDING VARIABLE VALUES: VP-EXPERT is able to retrieve variable values stored in text files, work sheets, and database files. It is also possible to send variable values to the same type of files just mentioned. This can be done at any time and with more than one variable at once. This feature is very desirable since it allows full interaction with external programs called by VP-EXPERT.

- SINGULAR OR PLURAL VARIABLES: The variables in VP-EXPERT can be singular or plural. A singular variable can have only one value assigned to it at one time, whereas a multiple variable can have more than one value at one time. A variable is considered to be singular by default unless otherwise specified by the PLURAL statement.

- CONFIDENCE FACTORS: Confidence factors are another feature of VP-EXPERT. In expert systems created with VP-EXPERT, numbers referred to as "confidence factors" are used to reflect varying degrees of certainty. These numbers can be entered in a rule conclusion or a user response to questions asked by VP-EXPERT during the consultation process. A confidence factor may also accompany the results of the consultation displayed by VP-EXPERT.

- CHAINING: This feature permits the use of knowledge bases that would otherwise be too large to be contained in memory. With this feature, it is possible to "chain" together two or more knowledge bases for use in a single consultation.

VP-EXPERT END USER FEATURES:

VP-EXPERT offers many user features. The main features are the ability to see the rules as they are scanned,in a slow mode if desired, ask how VP-EXPERT has arrived to a certain result, and check the value of different variables at the end of the consultation. Another important feature is the trace option, which when turned on, will generate a text or graphical tree which may later be viewed to see the path the inference engine has taken to solve the problem. VP-EXPERT also allows the user to change a certain answer and see the effect of that change on the result.

2.2.4 EXSYS [20]

EXSYS DEVELOPMENT FEATURES:

EXSYS is another rule-based expert system development tool. It stores its knowledge in the form of IF-THEN-ELSE rules. Unlike VP-EXPERT, rules are the only element in EXSYS. These rules are composed of conditions, conclusions, notes and references.

RULES

The rules in EXSYS are edited in a very systematic way enforced by the EXSYS editor. The developer has to specify QUALIFIERS and CHOICES which will later be used to build the rules. An example of one qualifier would be:

IF THE CARGO TYPE AND WEATHER CONDITION IS:

1. Non-timber and snow not thawing.
2. Timber and snow not thawing.
3. Either and snow thawing.

When building a rule, the developer can scan all such qualifiers and then pick the one needed for a certain rule. The qualifiers will be used to build the condition part of the rule. The choices would be used to build the conclusion part of the rule. A NOTE can be edited by the user when the IF-THEN-ELSE part has been completed. The note will appear to the user when a certain question related to that rule is asked. The purpose of the note is to explain or give certain information to the user in order to help him in giving a better answer to the question asked by EXSYS. The REFERENCE appears at the passing of a rule to explain where the conclusion to that rule came from.

- FORWARD AND BACKWARD CHAINING : Normally, EXSYS uses backward chaining as its rule scanning method. This method was discussed previously in VP-EXPERT. However, EXSYS also gives the option of using forward chaining to check the rules. This is possible by using the FORWARD command. With this command, EXSYS will test the rules in their order of appearance, with backward chaining to derive information as needed. The backward chaining could be completely turned off by using the NOBACKWARD option. This option forces EXSYS to not use backward chaining to derive information. However, the rules are checked in the order that the choices occur. With both the NOBACKWARD and FORWARD options purely forward chaining will be allowed. However, in this case all rules that derive information MUST occur in the knowledge base prior to the derived information being needed. If this is insured, the effect of FORWARD NOBACKWARD option on speeding the execution time can be very significant.

- CALLING EXTERNAL PROGRAMS : EXSYS can call external programs by using the RUN command. The file called must be an executable file with the extension .EXE or .COM. Batch files, however, cannot be called. If the external program is required to return a certain value for a variable, then it is called from that variable. This is done by using the RUN command at the beginning of the text defining that variable. Programs may also be called form qualifiers. In this case, the qualifier text starts with the RUN command. External programs can also be called from the THEN or ELSE part of a rule. However, data can be only passed to the program but can not be received back from it. Passing and receiving data will be discussed in more details in the next section.

- PASSING AND RECEIVING VARIABLE VALUES : In EXSYS, there is a difference between passing or receiving a single value and more than one value. There are two approaches to passing and receiving values in EXSYS. The first is the single value approach which deals with passing or receiving only one value. This can be done at any time in the program, through writing that value to a file RETURN.DAT or PASS.DAT. The second approach is a multi-variable approach. In this approach, data can only be passed from external programs to EXSYS. However, data cannot be passed out to external programs. It is also important to note that the external program passing these values can only be called at the beginning of the run before any other data is requested.

- SINGULAR OR PLURAL VARIABLES: In EXSYS all the variables may be plural. In other words EXSYS does not differentiate between a single and a plural variable. Thus when a user is asked to enter an answer form a list presented by EXSYS, he can enter more than one answer to one variable.

- CONFIDENCE FACTORS: EXSYS has three confidence factor scales. The first is from 0 to 10, second is -10 to +10, and finally 0 to 100 . These confidence factors, however, can only be used in the conclusion part of the rule as well as the final results given by EXSYS.

- MERGING EXPERT SYSTEMS: EXSYS can merge two expert systems together by adding the two rules of the two systems into on rule base.

- THE FASTER OPTION: EXSYS has a command called FASTER. This command rearranges the order of the rules in order to optimize the execution speed of the program. The speed can be improved up to 20 times faster using this option. This is especially desirable in the case of large rule bases.

EXSYS END USER FEATURES:

EXSYS offers many features similar to the ones offered by VP-EXPERT. These include seeing the rules as they are scanned, asking how EXSYS has arrived to a certain result, as well as the effect of changing one or more answers on the final results. Different features in EXSYS include the report generator which is somewhat similar to the trace option in VP-EXPERT. Another feature is the ability to keep the results of a previous consultation to compare with those of a new one once one or more answers have been changed. In both VP-EXPERT and EXSYS the user features seem to be very similar and the choice made in the next section will be mainly based on the development features.

2.3 Choice Of Expert System Development Tool

In the evaluation of the features of the shells surveyed, the needs of the expert system to be developed, ease of development and minimizing user induced errors will be kept in mind. The nature of the problem at hand, namely identifying and suggesting legal vehicle configurations, and the availability of a considerable amount of knowledge in the form of tables that can readily be represented in the form of rules, suggest the usefulness of a rule based shell. A hybrid shell or development tool was not seen necessary or advantageous for this specific application. For this reason, PERSONAL CONSULTANT and PERSONAL CONSULTANT PLUS were not evaluated any further and more consideration was given to evaluating and testing EXSYS and VP-EXPERT.

These two shells were available for practical evaluation by building a small prototype in both shells. The building of the prototype allowed a more tangible understanding of the features and drawbacks of each shell. A major requirement in this expert system is the ability to interface and exchange data with external programs. The nature of this data makes it, not only desirable, but necessary to be able to receive many variable values at one time. As discussed earlier, EXSYS allows such an exchange only at the beginning of the consultation process and not in the middle. This almost immediately implies that VP-EXPERT is the tool to be used.

Looking at the ease of development, the editor in VP-EXPERT offers more freedom for the developer in case of changing or adding rules. The text is directly and entirely accessible to the developer. Whereas in EXSYS, the rules may only be viewed one at a time and the changes made to one part of the rule at a time. This may be very cumbersome in the development stage where there are many changes to be made, as well as later when the expert system is being refined and expanded.

It was also mentioned that VP-EXPERT differentiates between single and plural variables whereas EXSYS allows any variable to be plural. If EXSYS asks the user this typical question used in this expert system :

THE CARGO TYPE AND WEATHER CONDITION IS:

1. Non-timber and snow not thawing.
2. Timber and snow not thawing.
3. Eithe. and snow thawing.

Nothing prevents the user from entering any combination of numbers in answer to this question. If the user enters 1,2, for example, then there will be a confusion in the consultation process as EXSYS checks the rules for both conditions. One condition may result in a legal configuration, whereas the other may result in an illegal one. Thus it is desirable to allow the user to make more than one choice only when allowed by the developer. This problem can be overcome by writing a rule that will check if there is more than one value assigned to the variable. However this requires extra effort on the part of the builder and if unnoticed may cause errors.

Finally, the actions block in VPEXPERT is a very desirable feature not found in EXSYS. This feature allows the builder to define the goals of the expert system using the FIND clause. This feature is not available in EXSYS where the entire rule base is scanned to come up with all possible true conclusions. Thus the builder has no control in defining what to look for.

Following this discussion, it was decided that for the purpose of the expert system at hand, VP-EXPERT would be the better choice.

2.4 Summary

In this chapter, introduction to expert systems and various definitions are presented. The major differences between expert systems and regular programs are discussed. Some common terms in expert systems are defined and explained. A general survey of expert systems development tools and shells is presented and a few P.C. based shells are studied more closely in order to choose a development shell or tool. A prototype is built using EXSYS and VP-EXPERT and VP-EXPERT is chosen as the development tool.

CHAPTER THREE

DEVELOPMENT OF KNOWLEDGE-BASED SYSTEM (KBS) VELSAS

3.1 Problem Formulation

The main problem addressed by this KBS is to establish whether a vehicle configuration suggested by the user is legal in the province of Québec. The problem is actually twofold. The first part of the expert system is concerned with determining whether a given vehicle is legal or not. In case the vehicle is determined to be illegal, the second part of the expert system suggests alternate configurations of the vehicle in order to make it legal. Both parts of the expert system rely heavily on a set of laws and regulations set by the Québec Ministry of Transportation [8,9]. In this thesis the vehicle configuration is fixed to be a tractor-semitrailer. However,the KBS developed can be extended to other types of vehicle configurations in a manner similar to the procedure outlined in this thesis.. What follows is a detailed description of the methods and logic followed in building this expert system. Where necessary, a typical example of a corresponding rule will be given.

3.2 Introduction to The Laws and Regulations

The purpose of the laws and regulations set by the government of Québec is to insure road user safety and protection of roadways and bridges. The laws cover the dimensions and loads of any vehicle that is to travel on public roads. Any vehicle that does not meet these regulations requires a special permit. For this reason, the laws and regulations were recently modified. The revised set of laws and regulations are set so as to minimize the number of special permits required. Vehicles with a model older than 1992 are, under certain conditions, allowed more loads than those with a newer model. What follows is a detailed representation of the different factors involved in determining the legality of a certain vehicle and the process of evaluating these aspects.

3.3 Determining Legal Vehicle Configurations

The legality of a vehicle depends on:

(a) Vehicle Dimensions.

(b) Axle Group Loads for Tractor Unit and Semitrailer Unit.

(c) Gross Vehicle Weight.

The methods followed for checking each of the above four categories and the way they are implemented in the expert system will be discussed in detail. The rules will be based on the information provided in the LOAD AND SIZE LIMITS GUIDE published by the Québec Ministry of Transport [9].

3.3.1 Vehicle dimensions:

(a) **LENGTH**

-Overall length: The maximum overall length for a tractor semitrailer is 23 m.

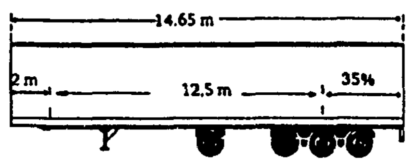
-Semitrailer length:

For a vehicle with a 1992 or newer model:

The maximum length for a semitrailer can be one of the following three:

(1) 10 m for all axle classes

(2) 14.65 m for axles with the requirements given below:

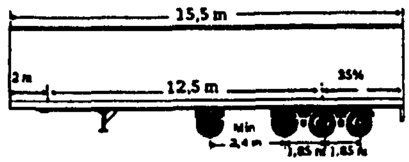


.The maximum kingpin offset is 2 m.

.The maximum distance between kingpin, or the center of the pivot of the coupling device, and center of rearmost axle is 12.5 m.

.Overhang should be a maximum of 35% of the distance between the center of the single, tandem or tridem axle and the kingpin center.

(3) 15.5 m for a single, tandem, or tridem axle and for a single and tridem axle with the following specification:



The maximum kingpin offset is 2 m. The maximum distance between kingpin and center of rearmost axle is 12.5 m.

Overhang should be a maximum of 35% of the distance between the center of the single, tandem or tridem axle and the kingpin center.

For a single and tridem axle, the minimum distance between the single axle and the tridem axle must be 2.4 m.

Axles are not more than 1.85 m. apart.

For a semitrailer with a model belonging to a year prior to 1992, the maximum length allowed is 14.65 m.

To illustrate how the above regulations would be implemented in the expert system, consider the following example. This rule represents case number 2 for the semitrailer length regulations.

example:

```
IF   semi_length <= 14.65  AND
     kingoffset <= 2.0  AND
     center_to_kingpin <= 12.5m  AND
     overhang <= (.35 * center_to_kingpin)  AND
     model=new
THEN semi_length_legality=legal;
```

2. HEIGHT

The maximum height of the vehicle, including cargo, cannot exceed 4.15 m.

3. WIDTH

The maximum width of the vehicle, including cargo,cannot exceed 2.6 m.

3.3.2 Axle loads for tractor unit and semitrailer unit:

The maximum load allowed on a tractor front axle is the least of the following three:

-total tire capacity (specified by the manufacturer).

-front axle capacity (specified by the manufacturer). This capacity cannot be less than 5500 kg. for a single front axle and 11000 kg.for a tandem or multiple front axle.

-load limit for axle class as specified by the government regulations.

The maximum load allowed on a tractor rear axle is the least of the following two:

-total tire capacity (specified by the manufacturer). The tire load should not exceed the limit of 11kg/mm of tire width.

-load limit for axle class as specified by the government regulations.

The maximum load allowed on a semitrailer axle group is the least of the following two:

-total tire capacity (specified by the manufacturer). The tire load should not exceed the limit of 11kg/mm of tire width.

-load limit for axle class as specified by the government regulations.

The load limit for each axle class is dependant on some or all of the following six parameters:

-axle class type

-axle class spacing

-load type

-year period

-vehicle model year

-whether the vehicle will be traveling only on autoroutes

The regulations used in building this expert system are included in Appendix A.

For the same axle class, a different spacing can sometimes increase or decrease the specified load limit. For example, a tridem axle with a spacing of 2.8 m is allowed to carry 23000 kg under certain loading conditions. The same axle under the same loading conditions but with a spacing of 3.0 m is allowed to carry 25000 kg.

The load type also affects the load rating. If a vehicle is carrying raw forest products, then it is usually allowed to carry more load than a vehicle carrying another type of load. The reason being that vehicles carrying raw forest products are not expected to travel long distances on the highway but rather make short trips between the forest and the plant.

Similarly, if a vehicle is operating during what is referred to as a thaw period, then the maximum load an axle can carry is reduced. The reason for this load restriction is that during the thaw period, the road strength decreases considerably, making it less resistant to the forces exerted by the vehicles passing on it. The decreased road strength results in more extensive road distortion and damage. Depending on the zone in which the vehicle is to travel, the thaw period extends from middle of March till the end of May (Fig 3.1).

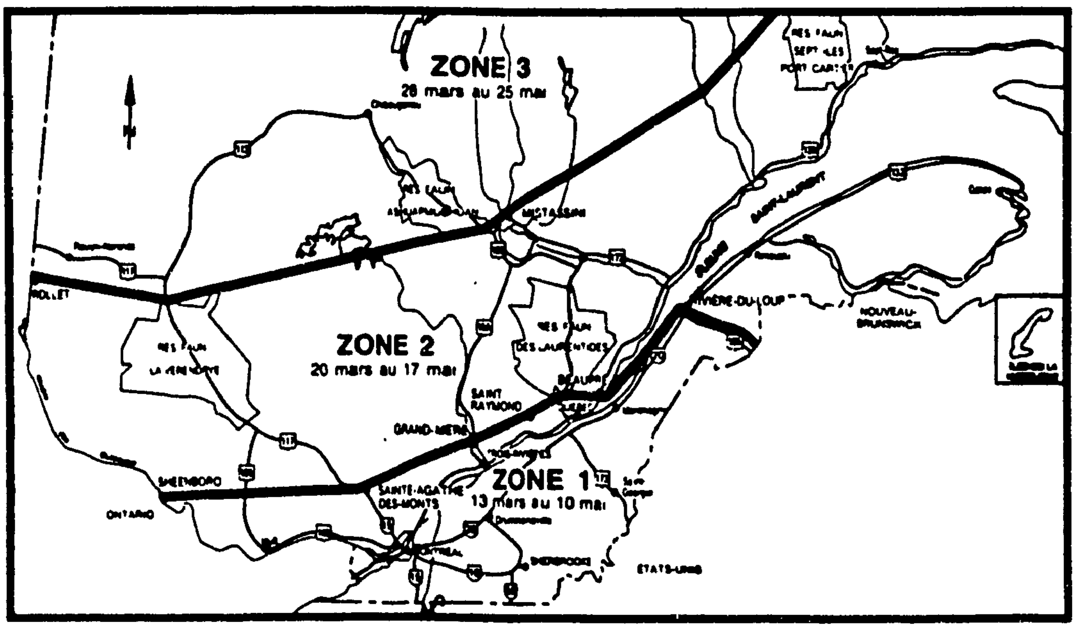


Figure 3.1 Thaw Period Zone Division [9]

The thaw period for the three zones is defined as follows:

Zone 1: March 13 to May 10

Zone 2: March 20 to May 17

Zone 3: March 28 to May 25

The model year of the vehicle can sometimes affect the load rating for the different axle groups. Since the regulations followed were recently modified in September of 1991, the Québec Ministry of Transportation has allowed a grace period during which vehicles with a model older than 1992 are sometimes allowed to carry more load than the newer vehicles. This rule does not apply for all axle types, year periods, and load types. The grace period extends until the end of 1994. Finally, if the vehicle will only be operating on autoroutes, then the semitrailer axle group is sometimes allowed to carry more load.

The problem of determining whether a certain vehicle meets the axle loads requirement is divided into two subproblems. The first deals with the legality of the tractor, the second deals with the legality of the semitrailer. In both cases, the actual axle loads on both the tractor and semitrailer are needed. For this purpose, at the beginning of its run, the expert system calls an external FORTRAN program called STATIC which calculates the required axle loads and writes them to a file which is read by VPEXPERT. This program will be described in section 3.2. What follows is an example of a rule in the expert system for determining maximum allowable semi-trailer axle group load. The parameters that define the limit are axle class, axle class spacing, loading condition and type of cargo and vehicle model. The rule in VPEXPERT would be:

```
IF   axle_type=tandem   AND
     axle_spacing<1.5   AND
     axle_spacing>=1.0  AND
     loading_condition=timber_no_snow  AND
     model=new
THEN trailer_max_load=17500;
```

3.3.3. Gross vehicle weight:

The maximum gross vehicle weight for a given tractor-semitrailer is the minimum of the following two values:

(1) The sum of the maximum allowable loads for each of the axle classes on the vehicle, namely tractor front, tractor rear and semitrailer axle class. This value will be referred to as **max_charge1**

(2) The gross weight limit of the vehicle as specified by the tables included in the vehicle load and size limits guide. This value will be referred to as **max_charge2**. The limit in this case, depends on the following:

- tractor rear axle type.
- semitrailer axle class and spacing.
- the distance between the frontmost semitrailer axle and tractor rear axle, in this study referred to as "a".

In calculating the first value, it is important to note that the maximum allowable load on the tractor front axle is not to exceed the following values:

- 5500 kg for a single axle
- 14000 kg for a tandem axle
- 13000 kg for a multiple axle

It is also important to note that until December 31, 1994, these front axle load limits do not apply, in a normal period, to tractor-semitrailers of a year model older than 1992 and have not been modified after October 1, 1991, to increase the axle load capacity.

3.3.4 Example on determining vehicle load legality

To best illustrate the different steps involved in determining a given vehicle's load legality, the following example is given. Consider the tractor-semitrailer shown below with the following characteristics:

- tractor and semitrailer year model : 1990
- tractor front axle: single

- tractor rear axle: tandem with a spacing of 1.52 m
- semitrailer axle group: single and tandem with a spacing of 4.88 m.
- distance "a": 4.3 m.
- front axle capacity: 7258 kg.
- tractor front tires total capacity: 5997 kg.
- tractor rear axle tires total capacity: 21047 kg.
- semitrailer axles' total tire capacity: 31570 kg.
- load type: non-timber or normal cargo

FIGURING THE RESPECTIVE MAXIMUM ALLOWABLE AXLE LOADS:

Tractor front axle:

The maximum load allowed on this axle is the lowest of the following three values:

(1) total tire capacity: 5997 kg;

(2) front axle capacity: 7258 kg;

(3) load limit for a single tractor front axle: 9000 kg.

Thus, the maximum allowable load for this axle is: 5997 kg. This value will be referred to as **tractorfmax** in this study and in the expert system.

Tractor rear axle:

The maximum load allowed on this axle is the lower of the following two values:

(1) total tire capacity: 21047 kg;

(2) load limit for a tandem axle with a spacing of 1.52 m.: 18000 kg. in normal period and 15000 kg. in thaw period.

Thus, the maximum allowable load on this axle is : 18000 kg. in normal period and 15000 kg. in thaw period.
This value will be referred to as **tractorrmax** in this study and in the expert system.

Semitrailer axle group

The maximum load allowed on this axle group is the lower of the following two values:

(1) total tire capacity: 31570 kg.

(2) load limit for a single and tandem axle group with a spacing of 4.88 m: 29000 kg in normal period and 22000 kg in thaw period.

Thus, the maximum allowable load on this axle group is: 29000 kg. in normal period and 22000 kg. in thaw period.
This value will be referred to as **trailermax** in this study and in the expert system.

FIGURING THE MAXIMUM ALLOWABLE GROSS WEIGHT:

Normal period:

The maximum allowable gross weight is the minimum of the following two values:

(1) The sum of the maximum allowable load for each of the above three axle groups, **max_charge1**, where :

max_charge1 = (trailermax + tractorfmax + tractorrmax)

In this case,

max_charge1 = 5997 kg + 18000 kg + 29000 kg = 52997 kg;

(2) The load limit, **max_charge2**, for a tractor semitrailer with a single tractor front axle, tandem rear tractor axle and a single and tandem trailer axle group and a spacing "a" of 4.3 m: 52000 kg.

Thus the maximum allowable gross weight for this vehicle in a normal year period is 52000 kg.

Thaw period:

The maximum allowable gross weight is the minimum of the following two values:

(1) The sum of the maximum allowable load for each of the above three axle groups: 5997 kg + 15000 kg + 22000 kg = 42997 kg.

(2) The load limit for a tractor semitrailer with a single tractor front axle, tandem rear tractor axle and a single and tandem trailer axle group and a spacing "a" of 4.3 m: 52000 kg.

Thus, the maximum allowable gross weight for this vehicle in a normal year period is 42997 kg.

3.4 Suggesting Legal Vehicle Configurations

This part of the expert system is required when it has been determined in the first part that the vehicle is illegal in one or more aspect. If the vehicle is illegal in one or more dimension requirement, the only suggestion given by the expert system is a statement of the maximum allowable dimension in each case. Similarly, if the tractor front or rear axle load is illegal, then the expert system will indicate the maximum allowable load in each case. The reason for this is that the changes suggested to the vehicle will be restricted to changes done on the semitrailer. If however, the vehicle breaks one or more of the following load requirements, then the procedure for suggesting possible changes is more involved. The different possibilities of illegal loads are given below. Each one will be explored in detail.

1. The semitrailer axle class load exceeds the maximum allowable axle class load specified in the regulations.

2. The semitrailer axle group load exceeds the maximum allowable total tire capacity.

3. The vehicle gross weight exceeds the maximum allowable gross weight specified in the regulations.

4. The vehicle gross weight exceeds the maximum allowable gross weight defined by the sum of the maximum allowable load for the three axle groups.

In the process of suggesting possible configuration changes, special attention will be given to insure that the changes made will be both minimal as well as practical. One should also make sure that in suggesting a certain change to satisfy a certain requirement, the other requirements will not be violated. Where more than one possible solution is available, the solutions will be listed in order of priority.

1. The semitrailer axle group load exceeds the maximum allowable axle group load given by the regulations. In this case, there are three possible solutions to consider.

The first solution is to shift the whole axle group back by a certain amount. This would reduce the load on the semitrailer axle group, while increasing it on the tractor axles. For this suggestion to be valid, the following two conditions should be satisfied. The first condition is that the load on the tractor front and rear axles should be legal, since as mentioned, this change would only add to the load on the tractor axles . The second condition is that the gross weight of the vehicle should not exceed the maximum allowable gross weight defined by the sum of the maximum allowable load for the three axle groups. If it does, then even if the semitrailer axle group is shifted back, the maximum allowable gross weight remains the same, and the vehicle would still be illegal. If these two conditions are satisfied, then it is possible to suggest to the user shifting the whole axle group back. It is important to note here that upon making this change, the user should again check for the legality of the tractor axle loads and gross weight specified in the tables in the regulations by consulting the expert system one more time.

The second possible solution is to increase the axle spacing. In some cases, increasing the axle spacing for a certain axle group will increase the maximum allowable load for that group. This solution is only useful, however; if the load on that axle group does not exceed the maximum allowable tire capacity. If it does, then the only choice left is to add one or more axles to the already existent axle group.

In adding one or more extra axles to the semitrailer axle group, one should take into consideration the total tire capacity. The new axle group tires' capacity should be equal to or greater than the actual axle group load. This can be insured by checking that the following condition is satisfied:

cap >= (trailer_max_load / number_of_tires)

where;

cap = load capacity of one tire,

trailer_max_load = maximum allowable load for the new proposed semitrailer axle group,

number_of_tires = number of tires on the proposed axle group.

Another factor that should be taken into consideration when choosing a new semitrailer axle group is the gross weight of the vehicle. If the gross weight of the vehicle exceeds the limit set by the sum of the three maximum allowable axle group loads, then the new semitrailer axle group should accommodate this extra load. To insure this, the following condition should be satisfied:

diff <= trailer_max_load

where,

diff = charge - tractorfmax- tractorrmax

charge = gross vehicle weight,

tractorfmax = maximum allowable load on the tractor front axle when calculating the maximum allowable total charge,

tractorrmax = maximum allowable load on the tractor front axle when calculating the maximum allowable total charge.

To clarify the process of satisfying the above conditions, consider the following example:

semitrailer axle group = tandem with a spacing of 3 m.

loading_condition = normal_no_snow

trailer_max_load = 20000 kg.

tractorfmax = 6000 kg.

tractorrmax=18000 kg

axle_load = 28000 kg.

max_charge1 = 44000 kg.

charge = 50000 kg.

semitrailer single tire capacity, trailer_cap= 3000 kg.

semitrailer tires' capacity = 24000 kg.

In this case, the actual load on the semitrailer axle group is 28000 kg., whereas the maximum allowable load is 20000 kg. The variable diff is equal to:

diff = 50000-6000 -18000 = 26000 kg.

The new semitrailer axle group should be chosen to satisfy the following conditions:

```
trailer_max_load >= axle load   or
trailer_max_load >= 28000,
trailer_max_load >= diff   or
trailer_max_load >= 26000,
3000 >= (trailer_max_load / number_of_tires)
```

Any rule with the specified loading conditions satisfying the above conditions will pass as a possible solution.

A typical rule that would pass in this case would be:

```
IF   loading_condition = normal_no_snow AND
     axle_load<=28000    AND
     diff<28000          AND
     cap>=(axle_load/16) AND
     cap>=(diff/16)
THEN trailer_configuration = four_or_more
     lowerspacing = 4.2;
```

Finally, the expert system should check that the maximum allowable gross weight limit of this new vehicle as specified by Table 2 in the regulations is not violated. If this condition is met, then the new axle configuration will pass as one possible solution.

When more than one solution is possible, the solutions will be listed in order of priority. Priority is given to the solution that requires the least change. Shifting the axle group would be the first, increasing the axle spacing would be the second, and finally adding one or more axles as required would be the last. It is important to note that in all these suggestions, the new axle group location should be such that the new value of the load on it is the same as the previous one. This is very important because the new axle group configuration is chosen based on that value. The new position of the axle group is calculated by the expert system using the available VPEXPERT math features. The method followed in calculating this value is described in section 3.2.

2. The semitrailer axle group load exceeds the maximum allowable total tire capacity. This case is very similar to the first case. The first requirement in this case is that the tires on the new axle group should accommodate the axle load. As mentioned in the previous case, the expert system should make sure that the new axle group satisfies the other load limits requirement. In this case, the semitrailer axle load should not exceed the maximum allowable axle load for the suggested configuration. The suggested semitrailer axle group should also satisfy the maximum allowable gross weight requirement defined by the sum of the maximum allowable load for the three axle groups as well as that defined for the new vehicle configuration in Table 2 of the regulations. When more than one solution is available, the solutions will

be given in order of priority.

3. The vehicle gross weight exceeds the maximum allowable gross weight specified in the regulations. In this case, the expert system will use the corresponding tables provided in the regulations to find possible configurations with a maximum allowable gross weight equal to or bigger than the actual gross weight.

example:

```
IF        charge <= 45500  AND
          charge > 44850
THEN      trailer_max_charge2_configuration = tandem
          lowerspacingmax_charge2 = 1.0
          amax_charge2 = 4.2;
```

Again, the expert system should check that the other load requirements, namely tire loads, axle loads and maximum allowable gross weight as defined by the sum of the maximum allowable load for the three axle groups, are not violated.

4. The vehicle gross weight exceeds the maximum allowable gross weight defined by the sum of the maximum allowable load for the three axle groups. The new semitrailer axle group should be chosen such that it will accommodate the excessive load that was illegal in the first case.

In order to find the suitable axle group configuration, the extra load is calculated using the following equation:

diff = charge - tractorfmax- tractorrmax

As in the first case, once the required diff value is calculated, the expert system finds the corresponding axle group configurations with a load limit equal to or greater than this value. Again, the expert system has to insure that these axle groups satisfy the load requirements for the tire capacity, the maximum allowable axle group load and the maximum allowable gross weight requirements for the new configuration.

3.5 Determining Axle Loads

From the previous section, it is clear that the expert system needs to know the respective axle loads for each of the axle sets. The three axle sets are the tractor front axle, tractor rear axle and semitrailer axle set. The axle loads are calculated by an external FORTRAN program STATIC that is called by VPEXPERT. Upon the finish of its run, STATIC will write the variable values to a file in a certain format required by VPEXPERT. VPEXPERT will then read in the required values and resume its consultation. The method used to calculate the required loads is based on the method suggested in [21]. A detailed description is given below.

Consider the tractor semitrailer in Figure 3.2. The vehicle can be divided into the tractor part and semitrailer part connected by the fifth wheel.

If the load on the fifth wheel is known, then the tractor front axle and rear axle loads can be easily calculated. The semitrailer however, poses a statically indeterminate problem. The method used for solving this problem is as follows.

Referring to Figure 3.3, the support points are numbered from left to right (1,2, ...N) and their position vectors (a_i's) are measured from the C.G. Note that the fifth wheel is identified as axle 1. It is first assumed that the load is equally divided on all the axles. In other words:

$$W_1 = W_2 = \ldots W_N = \frac{W}{N} \tag{3.1}$$

where N is the number of axles including the fifth wheel.

However, this solution does not necessarily satisfy the moment equilibrium condition. If the value of the residual moment is μ, then:

$$\mu = \frac{W}{N}\sum_{i=1}^{N} a_i \tag{3.2}$$

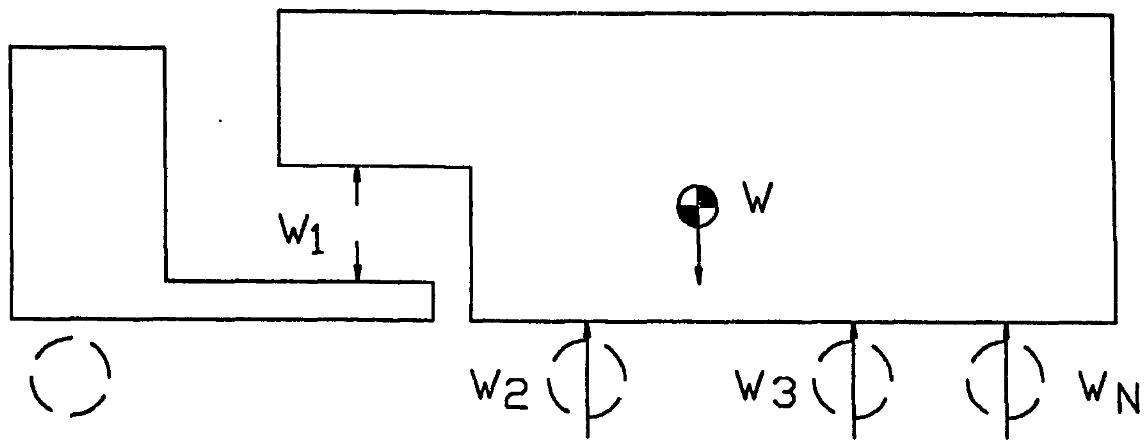


Figure 3.2 Loads on Tractor Semitrailer

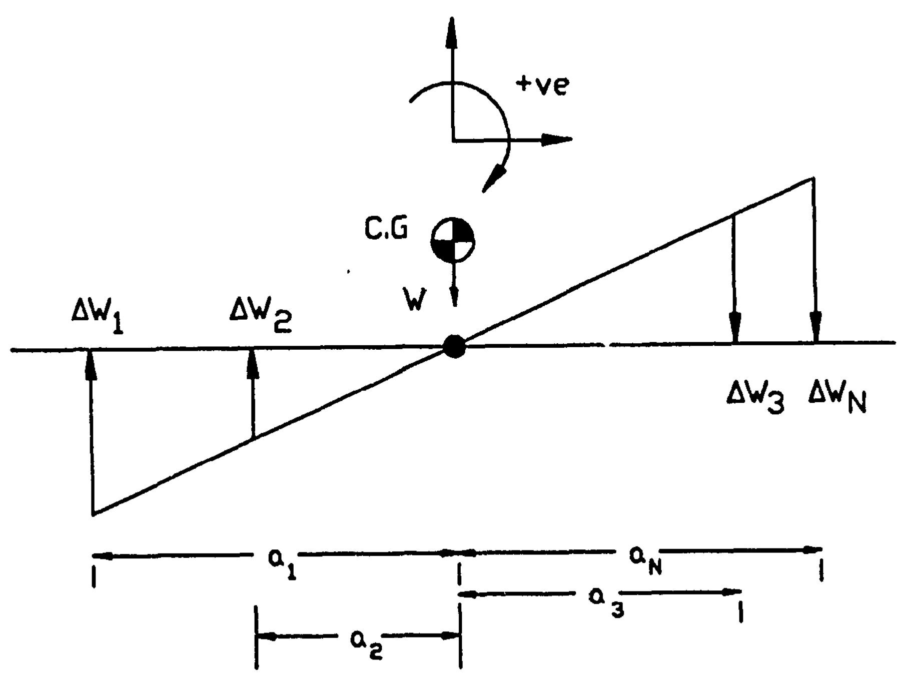


Figure 3.3 Distribution of Correcting Axle Loads

Now the axle loads should be adjusted by correcting loads ΔW_i, i = 1 to N so that the moment they generate about the center of gravity will be equal and opposite to the residual moment μ. In other words:

$$\sum_{i=1}^{N} a_i \Delta W_i = -\mu \qquad (3.3)$$

As seen in Figure 3.3, the correcting loads are assumed to be linearly distributed along the semitrailer so that their ratio is directly proportional to their distance to the center of gravity. Then:

$$\Delta W_i = \Delta W \left(\frac{a_i}{a_1} \right) \qquad i=2, \ldots N \qquad (3.4)$$

Substituting equation (3.4) in (3.3) we can calculate all the ΔW_i values. Once this is done, the sum of the correcting loads should be calculated to check for the following equality:

$$\sum_{i=1}^{N} \Delta W_i = 0 \qquad (3.5)$$

If this value is not equal to zero, then the remaining load is equally divided among the axles. Now these loads will be adjusted by a second set of correcting loads so that the moment they generate about the center of gravity will be equal to zero. This process is repeated iteratively until the resulting error is acceptable. In general, the error found after one iteration was very small, thus the loads were calculated using only one iteration.

3.6 Determining New Semitrailer Axle Positions

In some cases, the expert system will suggest a certain axle group configuration to be placed under the semitrailer in order to accommodate a certain load. As mentioned before, when the expert system chooses a certain axle group, it assumes that the load on the semitrailer axle group remains the same. Thus the new axle group position should be such that the load on the fifth wheel remains unchanged. The number of support points in the new axle group will either be one or two. In order to calculate the new axle group position the following method is used.

Consider the semitrailer body shown in Figure 3.4. The load on the fifth wheel W_1, and the axle group spacing "s_2", are known. However, the axle loads W_2 and W_3 and axle positions a_2 and a_3 are not known. Since the axle spacing "s_2" is known, then we have only three unknowns: W_1 and W_2 and the distance a_2 or a_3.

Assume that the load W is equally divided such that:

$$W_1 = W_2 = W_3 = \frac{W}{3} \tag{3.6}$$

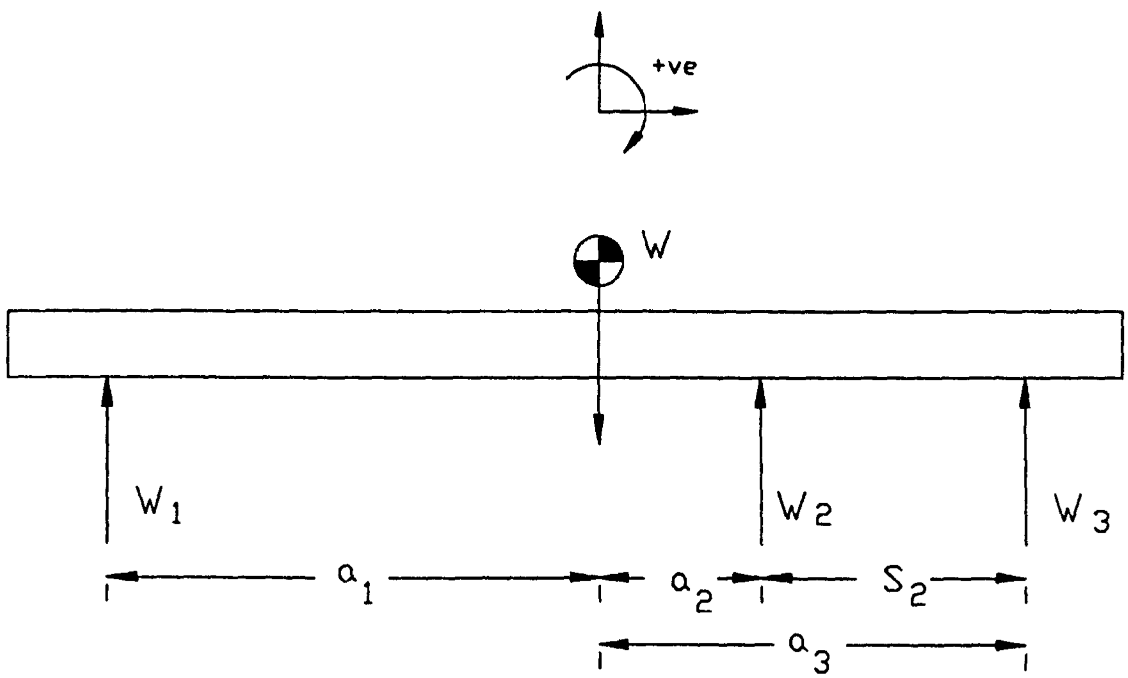


Figure 3.4 New Semitrailer Axle Group Position

Let the actual axle be:

$$W_1^{\bullet} = W_1 + \Delta W_1$$
$$W_2^{\bullet} = W_2 + \Delta W_2 \qquad (3.7)$$
$$W_3^{\bullet} = W_3 + \Delta W_3$$

The load $W_1^{\bullet}$ is known since it is equal to the load on the fifth wheel. Consequently, the correcting load ΔW_1 can be calculated.

Assuming that the correcting loads are linearly distributed along the structure, we can write:

$$\Delta W_2 = \frac{\Delta W_1 \ a_2}{a_1} \qquad (3.9)$$

$$\Delta W_3 = \frac{\Delta W_1 \ a_3}{a_1} \qquad (3.10)$$

The moment balance requires that the net moment generated by the correcting loads should be equal and opposite to the moment generated by the nominal loads. Thus we can write:

$$\Delta W_1 a_1 + \Delta W_2 a_2 + \Delta W_3 a_3 = -(W_1 a_1 + W_2 a_2 + W_3 a_3) \qquad (3.11)$$

substituting Equations 3.9 and 3.10 in equation 3.11 and noting that:

$a_3 = a_2 + s_2$

we can solve for a_2.

This process leads to the following second degree equation:

$$A\, a_2^2 + B\, a_2 + C = 0$$

where,

$$A = 2\Delta W_1$$

$$B = 2\Delta W_1 s_2 + 2W_1 a_1$$

$$C = \Delta W_1 s_2^2 + \Delta W_1 a_1^2 + W_1 a_1^2 + W_1 a_1 s_2$$

Once a_2 is found, the corresponding values for W_2 and W_3 can be calculated.

3.7 Summary

In this chapter, the requirements for the Knowledge-Based System (KBS): VELSAS are defined. The two basic requirements are identified as determining the dimension and load legality of a tractor semitrailer in Québec and to suggest certain modification to the vehicle if it is found to be illegal. The major goals needed to satisfy these requirements are presented and an example provided to show the steps taken by the expert system to reach its goals. Where necessary, examples of rules used in the KBS: VELSAS are provided. Finally, the methods used by the external programs to calculate axle loads and positions are described.

CHAPTER 4

ROLL STABILITY AND SENSITIVITY ANALYSIS FOR STEADY TURNING MANEUVERS

4.1 Problem Formulation

In the previous chapter, an expert system was developed to determine the legality of a given vehicle and to aid the user in arriving at a legal configuration. Another point of concern is the stability performance of a given vehicle. Once a satisfactory vehicle configuration has been reached, the user should be provided with some way of determining the stability of the vehicle. Different simulation models for predicting the stability behaviour of heavy articulated vehicles have been developed. These models vary in their complexity and capability. The static roll model was developed to calculate the rollover threshold of articulated vehicles during steady state turning. The yaw-roll model is used to study the directional and roll response of articulated vehicles undergoing steering maneuvers. The phase 4 model is used to study the braking and steering response of articulated vehicles. The increase in capability of a certain model is accompanied by an increase in complexity, number of parameters required and simulation time required. Of these models, the static roll model (SRM) is considered to provide a good indicator of the roll stability of a given vehicle while requiring the least simulation time and parameter input [4].

In the static roll model, it was found that the vehicle roll stability is sensitive to change in certain vehicle parameters. Several studies show that the rollover threshold is more sensitive to change in certain parameters than in others [4,5,6,7]. In these studies, to determine the effect of changing a certain parameter, it was necessary to rerun the program SRM every time a certain parameter value was changed. In this thesis, a mathematical sensitivity analysis approach is proposed. The purpose of this approach is to quickly estimate the new rollover threshold without having to rerun the program SRM. Thus the user will be provided with a way to evaluate the roll stability of the vehicle as well as quickly determine the effect of changing a certain parameter on the rollover threshold

4.2 Static Roll Model

A series of three progressively complicated roll stability models will be presented to illustrate the rollover process. Finally, a three-axle roll plane model [3], will be used to derive the sensitivity analysis equations.

4.2.1 Rigid block model [3]

Consider the rigid block model of a tractor semitrailer shown in Figure 4.1. In this model, the compliance of the tires and the suspension springs are neglected. If the vehicle is undergoing a steady turning maneuver with a lateral acceleration, a_y, then it is subjected to the following forces. A lateral tire force, $W \cdot a_y$, at the tire road interface, a centrifugal force, $W \cdot a_y$, vertical tire loads F1 and F2 and vertical load W. The centrifugal force, $W.a_y$, gives rise to the main overturning moment, $(W \cdot a_y \cdot h)$. The vertical loads F1 and F2 give rise to the stabilizing moment (F2-F1)T, produced by the side-to-side shift in the vertical tire loads F1 and F2. As the vehicle proceeds to roll, an additional overturning moment $(W.h.\phi)$ is produced by the lateral shift in the C.G. of the vehicle. The moment balance equation is given by:

$$W.h.a_y = (F2-F1)T - W.h.\phi \qquad (4.1)$$

Figure (4.2) shows the two moments on the right hand side of the equation as a function of the roll angle ϕ. For a small angle ϕ, the load W is completely transferred to the left tire so that F1 = 0.0 and F2 = W. At this point, the vehicle attains its maximum roll-resisting moment beyond which the vehicle is considered to be unstable. From Figure 4.2, the corresponding rollover threshold is expressed as:

$$a_y = \frac{T}{h} \qquad (4.2)$$

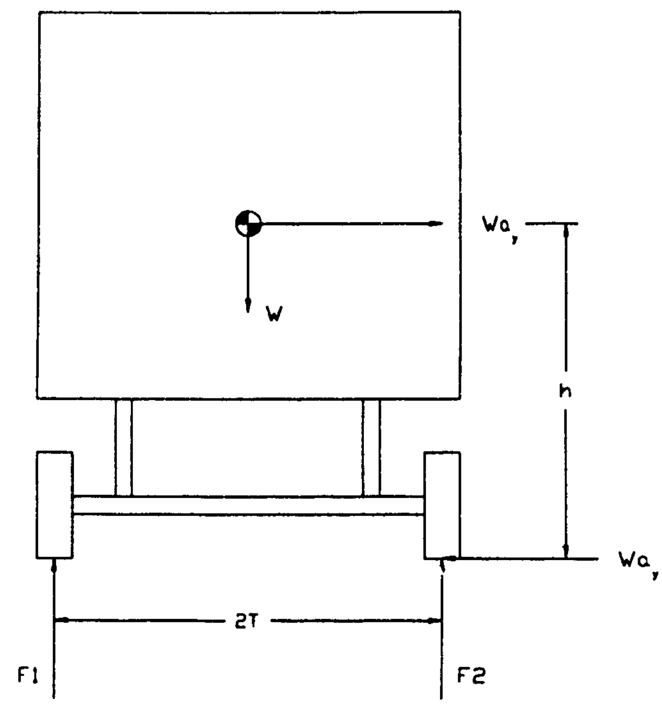


FIGURE 4.1 Rigid Block Model [3]

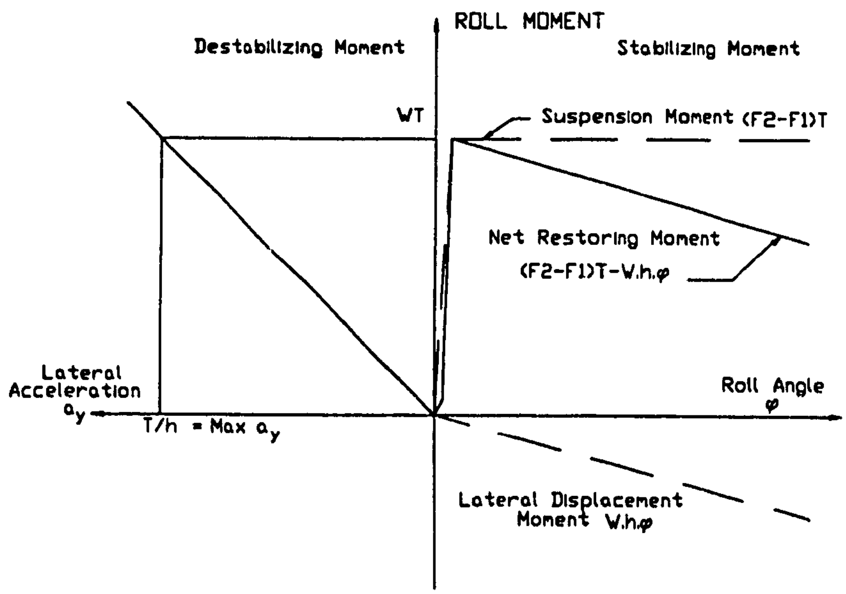


FIGURE 4.2 Roll Moment Diagram for Rigid Block Model [3]

4.2.2 Single-axle representation [3]

In this model, the compliance of the suspensions and the axles are included as shown in Figure (4.3). The axles, however, are lumped together and represented a single axle. In this model, the forces and moments acting on the vehicle are the same as in the rigid block model. However, it is to be noted that the angle at which the tires lift-off from the ground is not as small as that in the previous model. The magnitude of this angle depends upon the roll stiffness of the suspension and the tires. The magnitude of the maximum restoring moment, however, remains unchanged as shown in Figure (4.4). It can be seen in Figure (4.4) that the introduction of suspension and tire compliance into the model reduces the rollover threshold. By making the suspension infinitely stiff, we revert to the rigid block model. The new rollover threshold value for this model is given by:

$$a_y = \frac{T}{h} - \phi \tag{4.3}$$

4.2.3 Three-axle representation [3]

This model accommodates for the different suspension characteristics, track widths and C.G heights of the tractor front, tractor rear and semitrailer parts of the vehicle. In this model, the vehicle is represented by a single sprung mass which is supported by three composite axles: the tractor front axle, tractor rear axle and semitrailer axle.

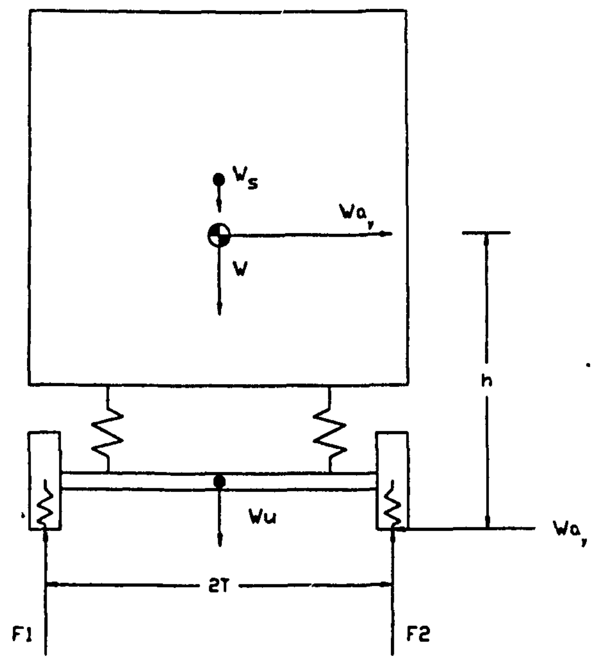


FIGURE 4.3 Single-Axle Model [3]

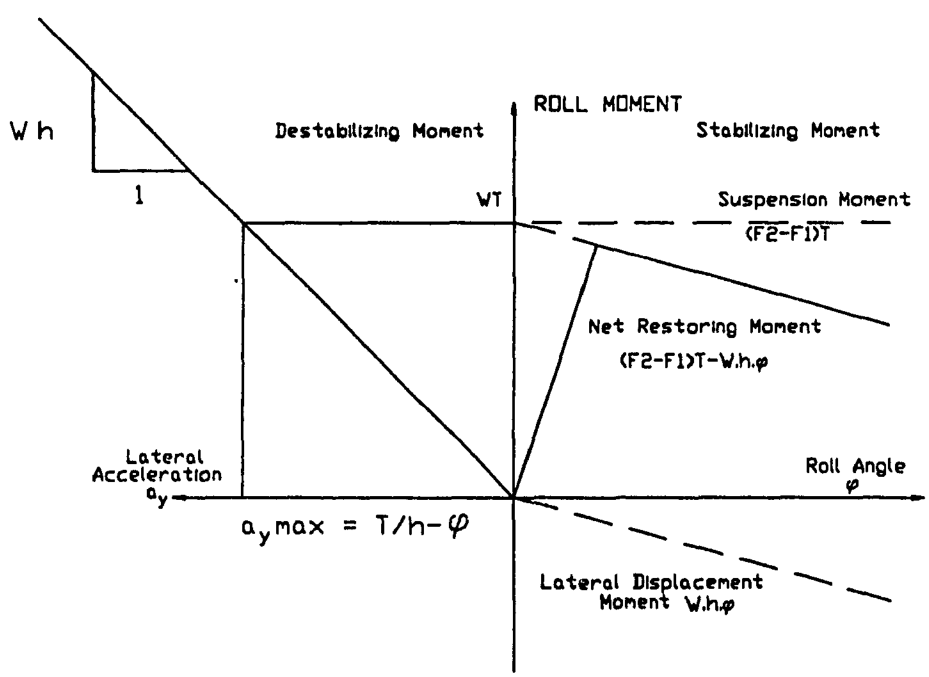


FIGURE 4.4 Roll Moment Diagram for Single-Axle Model [3]

If the loads carried by each of the composite axles are W1, W2 and W3 with respective half track widths of T1, T2 and T3, then the respective maximum roll resisting moments that can be produced by each axle will be, W1.T1, W2.T2 and W3.T3. In a typical tractor semitrailer, the suspension stiffness is the least for the tractor front axle, followed by the tractor rear axle and finally the semitrailer axle. If this is the case, then Figure (4.5) represents the moments acting on the vehicle. Figure (4.6) represents the net moment acting on the vehicle. From this figure, it is clear that the maximum restoring moment is attained at point B where the tractor rear tires lift-off. Beyond this point, the vehicle is considered to be unstable.

4.3 Roll Plane Model [3]

In this model, the tractor and trailer sprung masses are modeled as three rigid masses connected by torsional springs, Figure (4.7). The tractor front sprung mass is connected to the tractor rear sprung mass by a torsional spring, K_{FR}, that represents the tractor frame stiffness. The tractor rear sprung mass is connected to the trailer sprung mass by the fifth wheel which together with the structure compliance of the trailer body is represented by a torsional spring, K_5. The roll plane model is shown in Figure (4.8). In this model, the following assumptions are made. The sprung masses roll about their respective roll centers which are at a fixed distance beneath the sprung

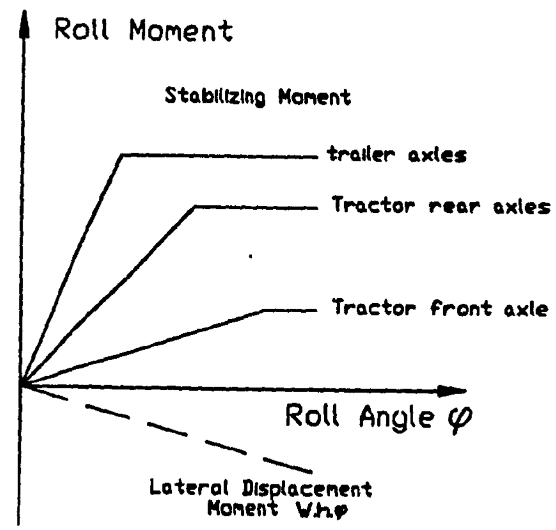


FIGURE 4.5 Roll Moment Diagram for Three-Axle Model [3]

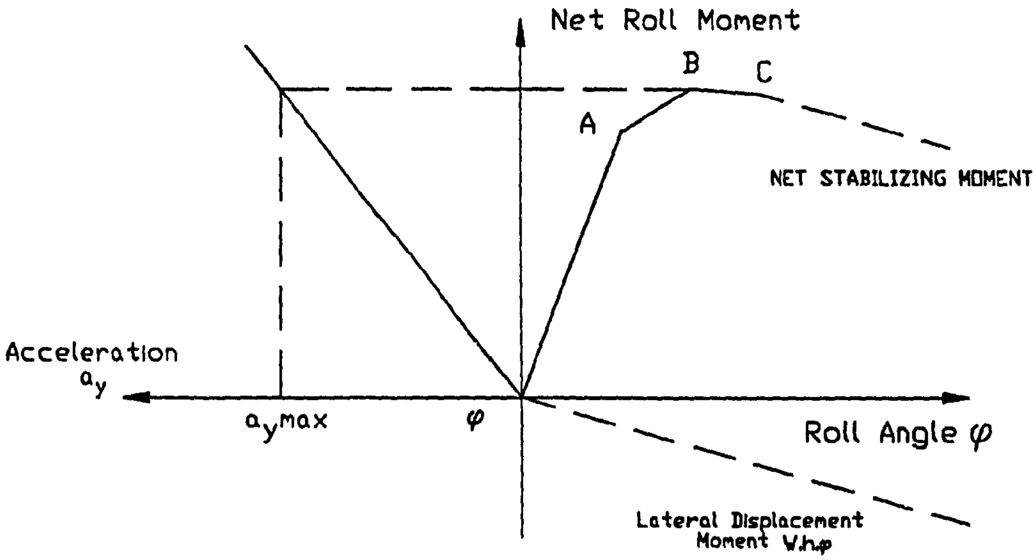


FIGURE 4.6 Net Roll Moment Diagram for Three-Axle Model [3]

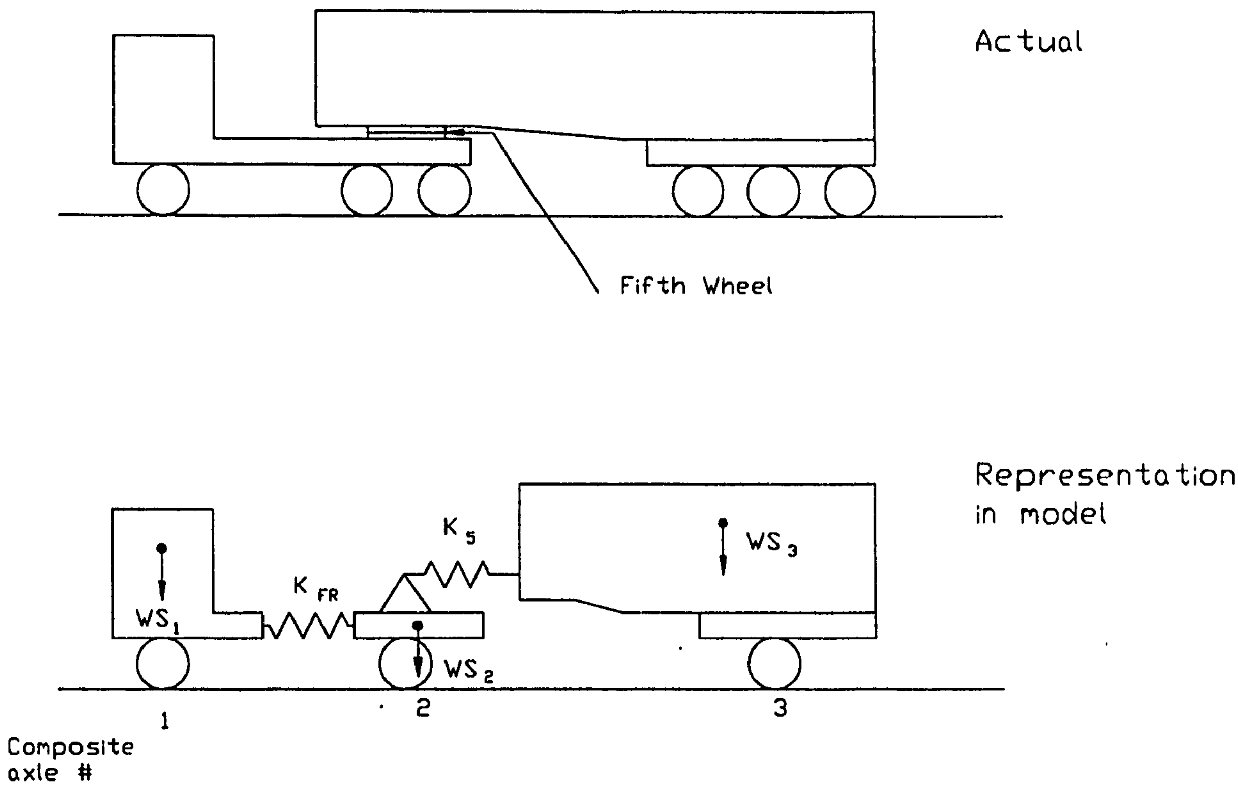


FIGURE 4.7 Side View of the Static Roll Plane Model [3]

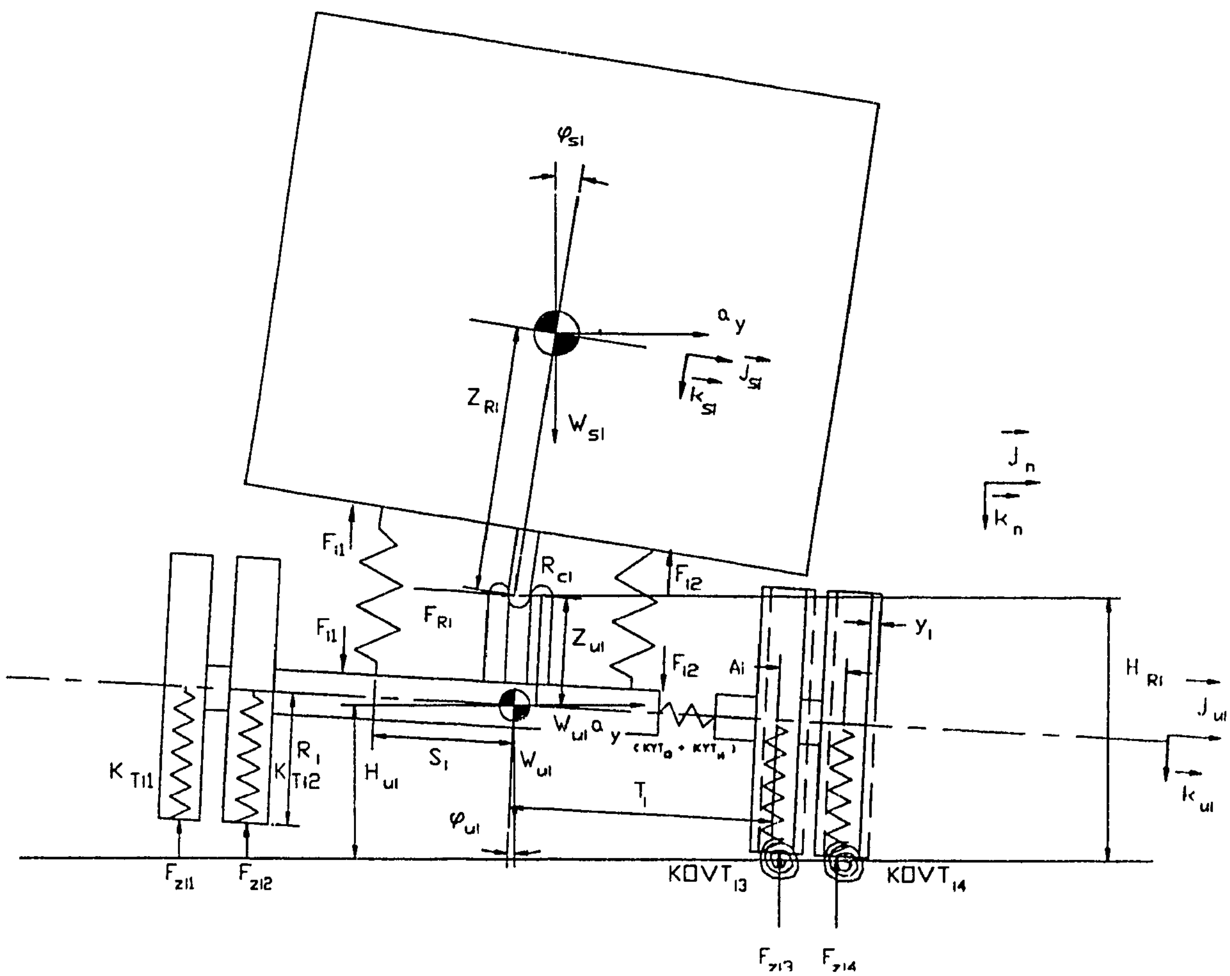


FIGURE 4.8 Rear View of the Static Roll Plane Model [3]

mass center of gravity but are permitted to slide with respect to the axles along the vertical axes, $\vec{k}_{ui}$. The suspension springs can only transmit compressive or tensile forces and they remain perpendicular to the axles. The suspension springs are considered to be linear about their operating point. Each spring is represented by a force-deflection table which is used to calculate the spring rate at the desired operating point. The roll angles of the sprung masses and axles are small, so that the small angles assumptions $\sin \phi = \phi$ and $\cos \phi = 1.0$ can be used. For complete details of the model and assumptions, refer to [3].

A total of fifteen equations are needed to define the static equilibrium condition of a vehicle [3]. These are obtained by balancing the moments acting on the sprung and unsprung masses and the forces acting on the suspensions and tires. The fifteen equations are divided into:

(a) Three roll moment equations, one for each of the sprung masses.

(b) Three roll moment equations, one for each of the unsprung masses.

(c) Three vertical force equations for the suspension springs, one for each composite axle.

(d) Three vertical force equations for the tires, one for each composite axle.

(e) Three lateral force equations for the tires, one for each composite axle.

Although the equations have been derived and presented in [3], for the purpose of the sensitivity analysis, they are rederived here and presented as follows.

4.3.1 Rolling moment equations for the sprung masses

The roll moments acting on the first sprung mass are due to spring forces, F_{11} and F_{12}, vertical load acting on the frame, W_{FR} ($W_{FR}=W_5+ W_{S2}+ W_{U2}- WAXL_2$), moment transmitted through the frame, M_{FR}, and the lateral force acting through the roll center, FR_1. Thus the roll moment equation for the first sprung mass will be:

$$F_{11}\left[S_1+ Z_{R1}\sin(\phi_{S1}- \phi_{U1})\right] - F_{12}\left[S_1- Z_{R1}\sin(\phi_{S1}- \phi_{U1})\right]$$
$$+ W_{FR}(a_y\cos \phi_{S1} - \sin \phi_{S1})Z_{FR1}+ M_{FR}$$
$$- F_{R1}\ Z_{R1}\cos(\phi_{S1}- \phi_{U1}) = 0.0 \qquad (4.4)$$

Using the small angle assumption, the above equation becomes:

$$(F_{11}- F_{12})S_1+ (F_{11}+ F_{12})Z_{R1}(\phi_{S1}- \phi_{U1})$$
$$+ W_{FR}(a_y- \phi_{S1})Z_{FR1}+ M_{FR} - F_{R1}\ Z_{R1} = 0.0 \qquad (4.5)$$

where,

$$F_{11} = K_{11}\left[\Delta\bar{Z}_{U1}-S_1(\phi_{S1}- \phi_{U1})\right]$$
$$F_{12} = K_{12}\left[\Delta\bar{Z}_{U1}+S_1(\phi_{S1}- \phi_{U1})\right] \qquad (4.6)$$

$$F_{R1}= W_{S1}(a_y-\phi_{U1}) \qquad (4.7)$$

$$F_{11} + F_{12} = W_{S1}(1 + a_y \phi_{U1}) \tag{4.8}$$

$$W_{S1} = WAXL_1 - W_{U1} \tag{4.9}$$

If we change the sprung mass angle ϕ_{S3} by a small amount $\Delta\phi_{S3}$, and for a small deviation from the equilibrium condition, the corresponding change in equation (4.5) will be:

$$(\Delta F_{11} - \Delta F_{12}) S_1 + (\Delta F_{11} + \Delta F_{12}) Z_{R1} (\phi_{S1} - \phi_{U1})$$
$$+ (F_{11} + F_{12}) Z_{R1} (\Delta\phi_{S1} - \Delta\phi_{U1}) + W_{FR}(\Delta a_y - \Delta\phi_{S1}) Z_{FR1}$$
$$+ \Delta M_{FR} - \Delta F_{R1} \; Z_{R1} = 0.0 \tag{4.10}$$

where,

$$\Delta F_{11} = K_{11}\left[\Delta z_{U1} - S_1(\Delta\phi_{S1} - \Delta\phi_{U1})\right]$$

$$\Delta F_{12} = K_{12}\left[\Delta z_{U1} + S_1(\Delta\phi_{S1} - \Delta\phi_{U1})\right] \tag{4.11}$$

$$\Delta F_{11} + \Delta F_{12} = W_{S1}(\Delta a_y \phi_{U1} + a_y \Delta\phi_{U1}) \tag{4.12}$$

$$\Delta F_{R1} = (WAXL_1 - W_{U1})(\Delta a_y - \Delta\phi_{U1}) \tag{4.13}$$

Substituting the above three equations into equation (4.10), the rolling moment equation for the first sprung mass becomes:

$$(K_{11} - K_{12}) S_1 \Delta Z_{U1} - (K_{11} + K_{12}) S_1^2 \Delta\phi_{S1} + (K_{11} + K_{12}) S_1^2 \Delta\phi_{U1}$$
$$- (WAXL_1 - W_{U1}) \Delta a_y Z_{R1} + (WAXL_1 - W_{U1}) \Delta\phi_{U1} Z_{R1}$$
$$+ (WAXL_1 - W_{U1}) Z_{R1} (\phi_{S1} - \phi_{U1}) (\Delta a_y \phi_{U1} + a_y \Delta\phi_{U1})$$
$$+ (F_{11} + F_{12}) Z_{R1} (\Delta\phi_{S1} - \Delta\phi_{U1}) + K_{FR} (\Delta\phi_{S2} - \Delta\phi_{S1})$$
$$+ W_{FR} Z_{FR1} \Delta a_y - W_{FR} Z_{FR1} \Delta\phi_{S1} = 0.0 \tag{4.14}$$

The moments on the second sprung mass are similar to those for the first sprung mass with the following two additional moments. The moment M_5 transmitted by the fifth wheel,

$$M_5 = K_5(\phi_{S3} - \phi_{S2})$$

and the moment MW_5 due to the fifth wheel load W_5,

$$MW_5 = W_5 Z_{52}(a_y \cos(\phi_{S2}) - \sin(\phi_{S2}))$$

Thus the rolling moment equation for the second sprung mass for a small change from a given equilibrium condition is:

$$\begin{aligned}
&(K_{21} - K_{22}) S_2 \Delta Z_{U2} - (K_{21} + K_{22}) S_2^2 \Delta\phi_{S2} + (K_{21} + K_{22}) S_2^2 \Delta\phi_{U2} \\
&- (WAXL_2 - W_{U2}) \Delta a_y Z_{R2} + (WAXL_2 - W_{U2}) \Delta\phi_{U2} Z_{R2} \\
&+ (WAXL_2 - W_{U2}) Z_{R2} (\phi_{S2} - \phi_{U2}) (\Delta a_y \phi_{U2} + a_y \Delta\phi_{U2}) \\
&+ (F_{21} + F_{22}) Z_{R2} (\Delta\phi_{S2} - \Delta\phi_{U2}) - K_{FR} (\Delta\phi_{S2} - \Delta\phi_{S1}) \\
&- W_{FR} Z_{FR2} \Delta a_y + W_{FR} Z_{FR2} \Delta\phi_{S2} + K_5 (\Delta\phi_{S3} - \Delta\phi_{S2}) \\
&- W_5 (\Delta a_y - \Delta\phi_{S2}) Z_{52} = 0.0 \qquad (4.15)
\end{aligned}$$

Similarly, the moments on the third sprung mass are due to the spring forces, the lateral forces acting through the roll center, moment transmitted by the fifth wheel and moment due to the load on the fifth wheel. Thus the rolling moment equation for the third sprung mass for a small change from a given equilibrium condition is:

$$(K_{31} - K_{32})S_3\Delta Z_{U3} - (K_{31} + K_{32})S_3^2\Delta\phi_{S3} + (K_{31} + K_{32})S_3^2\Delta\phi_{U3}$$
$$- (WAXL_3 - W_{U3})\Delta a_y Z_{R3} + (WAXL_3 - W_{U3})\Delta\phi_{U3}Z_{R3}$$
$$+ (WAXL_3 - W_{U3})Z_{R3}(\phi_{S3} - \phi_{U3})(\Delta a_y\phi_{U3} + a_y\Delta\phi_{U3})$$
$$+ (F_{31} + F_{32})Z_{R3}(\Delta\phi_{S3} - \Delta\phi_{U3}) - K_5(\Delta\phi_{S3} - \Delta\phi_{S2})$$
$$- W_5(\Delta a_y - \Delta\phi_{S3})Z_{53} = 0.0 \qquad (4.16)$$

4.3.2 Rolling moment equations for the unsprung masses

Since the springs and tires attached to the three axles are all similar, one general equation can be derived to describe the roll moment for the unsprung masses. The moments acting on each of the three unsprung masses are due to the spring forces F_{i1} and F_{i2}, vertical tire forces F_{zij}, lateral forces at the roll center FR_i, as well as the lateral tire forces F_{yi} and roll resisting moments OVT_{i3} and OVT_{i4} generated at the outer tires. The general roll moment equation for the unsprung mass i is:

$$-(F_{i1} - F_{i2})S_i + (F_{zi1} + F_{zi2} + F_{zi3} + F_{zi4})R_i\phi_{Ui}$$
$$+ (F_{zi1} - F_{zi4})(T_i + A_i)\cos\phi_{Ui} + (F_{zi2} - F_{zi3})T_i\cos\phi_{Ui}$$
$$- (F_{zi3} + F_{zi4})y_i\cos\phi_{Ui} + FR_iZ_{Ui} + F_{yi}H_{Ui}$$
$$+ OVT_{i3} + OVT_{i4} = 0.0 \qquad (4.17)$$

Using the small angle assumption, for a small change in roll angle $\Delta\phi_{S3}$, and for a small deviation from the equilibrium condition, equation (4.17) can be written as:

$$-(\Delta F_{i1} - \Delta F_{i2})S_i + (\Delta F_{zi1} + \Delta F_{zi2} + \Delta F_{zi3} + \Delta F_{zi4})R_i\phi_{Ui}$$
$$+ (\Delta F_{zi1} - \Delta F_{zi4})(T_i + A_i) + (\Delta F_{zi2} - \Delta F_{zi3})T_i$$
$$- (\Delta F_{zi3} + \Delta F_{zi4})y_i - (F_{zi3} + F_{zi4})\Delta y_i + FR_i\Delta Z_{Ui} + \Delta FR_i Z_{Ui}$$
$$\Delta F_{yi}H_{Ui} + F_{yi}\Delta H_{Ui} + \Delta OVT_{i3} + \Delta OVT_{i4} = 0.0 \qquad (4.18)$$

where,

$$\Delta F_{zi1} = -KT_{i1}\Big[(T_i + A_i)\Delta\phi_{Ui} - \Delta H_{Ui}\Big]$$

$$\Delta F_{zi2} = -KT_{i2}\Big[T_i\ \Delta\phi_{Ui} - \Delta H_{Ui}\Big]$$

$$\Delta F_{zi4} = KT_{i3}\Big[(T_i + y_i)\Delta\phi_{Ui} - \Delta y_i\phi_{Ui} + \Delta H_{Ui}\Big]$$

$$\Delta F_{zi4} = KT_{i4}\Big[(T_i + A_i + y_i)\Delta\phi_{Ui} - \Delta y_i\phi_{Ui} + \Delta H_{Ui}\Big] \qquad (4.19)$$

where i = 1, 2 and 3 correspond to the tractor front, tractor rear and trailer suspensions respectively, and

$$\Delta OVT_{i3} = -\ KOVT_{i3}\Delta\phi_{Ui}$$
$$\Delta OVT_{i4} = -\ KOVT_{i4}\Delta\phi_{Ui} \qquad (4.20)$$

Substituting equations (4.19) and (4.20) into equation (4.18), the three rolling moment equations for the unsprung masses become:

$$(K_{i1} + K_{i2})S_i^2\Delta\phi_{Si} - [(K_{i1} + K_{i2})S_i^2 - WAXL_iR_i$$
$$- (WAXL_i - W_{Ui})Z_{Ui} + KOVT_{i3} + KOVT_{i4} + KT_{i1}(T_i + A_i)^2$$
$$+ KT_{i2}T_i^2 + KT_{i3}(T_i + y_i)^2 + KT_{i4}(T_i + A_i + y_i)^2]\Delta\phi_{Ui}$$
$$+ [-(K_{i1} - K_{i2})S_i + (WAXL_i - W_{Ui})(a_y - \phi_{Ui})]\Delta z_{Ui}$$
$$+[(KT_{i1} - KT_{i4})(T_i + A_i) + (KT_{i2} - KT_{i3})T_i$$
$$- (KT_{i3} + KT_{i4})y_i + WAXL_ia_y]\Delta H_{Ui} - [(WAXL_i - W_{Ui})HR_i$$
$$+ W_{Ui}H_{Ui}\ ]\Delta a_y - \Big[F_{zi3} + F_{zi4} + [(KT_{i3} + KT_{i4})(T_i + y_i)$$
$$+ KT_{i4}\ A_i]\phi_{Ui}\Big]\Delta y_i = 0.0 \qquad (4.21)$$

where i = 1, 2 and 3 correspond to the tractor front axle, tractor rear axle and trailer axle respectively.

4.3.3 Vertical force equations for the suspension springs:

For equilibrium along the $\vec{k}_{ui}$ axis, the following condition must be satisfied:

$$F_{i1} + F_{i2} = (WAXL_i - W_{Ui})\cos\phi_{Ui} + (WAXL_i - W_{Ui})a_y \sin\phi_{Ui} \qquad (4.22)$$

Using the small angle assumption, for a small change $\Delta\phi_{S3}$, and for a small deviation from the equilibrium condition, equation (4.22) can be written as:

$$(K_{i1} + K_{i2})\Delta Z_{Ui} - (K_{i1} - K_{i2})S_i\Delta\phi_{Si} + (K_{i1} - K_{i2})S_i\Delta\phi_{Ui}$$
$$- (WAXL_i - W_{Ui})\phi_{Ui}\Delta a_y - (WAXL_i - W_{Ui})a_y\Delta\phi_{Ui} = 0.0 \qquad (4.23)$$

where i = 1, 2 and 3 correspond to the tractor front, tractor rear and trailer suspensions respectively.

4.3.4 Vertical force equations for the tires:

Since the vertical load carried by each composite axle is assumed to remain constant, the vertical tire forces are equal to the load carried by the axle. Thus we can write:

$$F_{zi1} + F_{zi2} + F_{zi3} + F_{zi4} = WAXL_i \qquad (4.24)$$

Looking at the effect of a small change in the roll angle ϕ_{S3}, and for a small deviation from the equilibrium condition, the above equation becomes:

$$\Delta F_{zi1} + \Delta F_{zi2} + \Delta F_{zi3} + \Delta F_{zi4} = 0.0 \tag{4.25}$$

Substituting equation (4.19) into the above equation, we get:

$$\begin{aligned}&[(-KT_{i1} + KT_{i4})(T_i + A_i) + (-KT_{i2} + KT_{i3})T_i \\ &+ (KT_{i3} + KT_{i4})y_i]\Delta\phi_{Ui} + (KT_{i1} + KT_{i2} + KT_{i3} + KT_{i4})\Delta H_{Ui} \\ &+ (KT_{i3} + KT_{i4})\phi_{Ui}\Delta y_i = 0.0\end{aligned} \tag{4.26}$$

where i=1,2 and 3 correspond to the tractor front, tractor rear and trailer tires respectively.

4.3.5 Lateral force equations for the tires:

In the model, it was assumed that the entire lateral force is taken up by the external tires. If the centroid of normal pressure is displaced by y_i, then the lateral force F_{yi} acting on the external tires of the i^{th} axle is equal to:

$$F_{yi} = (KYT_{i3} + KYT_{i4})y_i \cos \phi_{Ui} \tag{4.27}$$

Noting that $F_{yi} = WAXL_i a_y$, for a small change in the roll angle ϕ_{S3}, and for a small deviation from the equilibrium condition, equation (4.27) becomes:

$$WAXL_i \Delta a_y - (KYT_{i3} + KYT_{i4})\Delta y_i = 0.0 \quad (4.28)$$

where i=1,2 and 3 correspond to the tractor front, tractor rear and trailer tires respectively.

Thus equations (4.14), (4.15), (4.16) and the three equations in each of (4.21), (4.23), (4.26) and (4.28) constitute the fifteen equations needed to describe the roll response of a tractor semitrailer during steady state turning.

These fifteen equations can be written in the following general matrix form:

$$[\bar{A}]\{\overline{\Delta x}\} = \{\bar{B}\}\Delta\phi_{S3} \quad (4.29)$$

where, $[\bar{A}]$ is a (15×15) coefficient matrix, $\{\bar{B}\}$ is a vector of (15×1), and $\{\overline{\Delta x}\}$ is a vector of (15×1) response variables, where

$$\{\overline{\Delta x}\} = (\Delta a_y, \Delta\phi_{S1}, \Delta\phi_{S2}, \Delta\phi_{U1}, \Delta\phi_{U2}, \Delta\phi_{U3}, \Delta z_{U1}, \Delta z_{U2}, \Delta z_{U3}, \Delta H_{U1}, \Delta H_{U2}, \Delta H_{U3}, \Delta y_1, \Delta y_2, \Delta y_3)^T \quad (4.30)$$

In this model, the above fifteen equations are solved for an input roll angle increment $\Delta\phi_{S3}$. For each increment of $\Delta\phi_{S3}$, $[\bar{A}]$ and $\{\bar{B}\}$ are updated and the vector $\{\overline{\Delta x}\}$ is calculated, until the tires on one side of the tractor rear and trailer axles lift-off the ground. At this point the vehicle is considered to have reached an unstable position and the computation is terminated. The highest lateral acceleration achieved to this point is called the rollover threshold.

4.4 Parametric Sensitivity Analysis

It is to be noted that $[\bar{A}]$ and $\{\bar{B}\}$ in equation (4.29) are functions of the parameters of the vehicle and thus a change in some of these parameters may affect the value of rollover threshold. Several studies have been done to determine the effect of changing a certain parameter on the rollover threshold of a given vehicle [4,5,6]. These studies have shown some parameters to be more sensitive than others.

In [4], sensitivity analysis was carried out in an effort to simplify the SRM model. The parameters examined are the tractor frame torsional stiffness, tractor frame coulomb friction, fifth-wheel compliance and fifth-wheel lash. In the study, both the individual and combined effect of changing these parameters was examined. In both cases, the change in the parameters had no effect on the rollover threshold.

In [5], sensitivity analysis was carried out using two sets of typical parameter inputs which are based on varying the parameters by +10% and -10% from the baseline data. Table (4.1) gives a list of parameters which were found to be most sensitive. The corresponding change in lateral acceleration at which the first wheel lifts off is also given. The other parameters were found to have an effect of less than ± 2% for a variation of ± 10% .

In the same study, the effect of certain parameters on a vehicle rollover threshold was analyzed by taking into consideration the precision at which each parameter could be best determined at a roadside station. Table (4.2) gives a list of the most sensitive vehicle parameters, their best estimated precision and the resulting errors in the rollover threshold. It is important to note that the rollover threshold in this study was the lateral acceleration at which the first wheel lifts off.

In [6], sensitivity analysis of a number of parameters was carried out to determine their effect on the rollover threshold. The parameters were divided into three groups. The first group includes parameters which have no effect on determining the rollover threshold. These parameters are:

Table 4.1

Effect of ± 10% change in most sensitive vehicle parameters on rollover threshold [5]

Vehicle Parameter	Percent Change in Lateral Acceleration	
	Effect of -10% Change	Effect of +10% Change
Trailer sprung mass C.G. height	+12.8%	-10.5%
Trailer sprung mass	+ 7.9%	- 3.9%
Trailer track width	- 6.0%	+ 4.9%
Trailer axle load	- 5.8%	+ 5.2%
Tractor rear spring spacing	- 3.9%	+ 4.3%
Height of tractor rear suspension roll center	- 2.7%	+ 2.5%
Tractor rear axle track width	- 2.3%	+ 1.8%
Trailer axle dual tire spacing	- 2.0%	+ 1.8%

Table 4.2

Errors on the vehicle rollover threshold (percent change in lateral acceleration) resulting from the best estimated precision on most sensitive parameters [5]

Vehicle Parameter	Percent Change in Parameter	Absolute Change in lat. acc.
Trailer sprung mass C.G. height	10%	12.35%
Tractor rear axle spring spacing	5%	2.16%
Tractor front sprung mass C.G. height	10%	1.85%
Height of tractor rear axle roll center	5%	1.34%
Tractor rear spring table	5%	0.93%
Trailer rear spring table	10%	0.62%
Dual tire spacing on trailer axle	4%	0.82%
Trailer track width	1%	0.60%
Height of trailer axle roll center	5%	0.72%
Trailer sprung mass	1%	0.39%
Height of tractor front axle roll center	5%	0.62%
Tractor rear sprung mass C.G. height	10%	0.62%
Tractor front spring spacing	5%	0.62%
Trailer spring spacing	5%	0.31%
Tractor front spring table	10%	0.62%
Dual tire spacing on tractor rear axle	4%	0.25%
Tractor rear track width	1%	0.23%

1- Tractor frame torsional stiffness, K_{FR} .

2- Coulomb friction present in the tractor frame, C_{FR} .

3- Overturning stiffness of the tires, K_{OVTi} .

4- Lash in the fifth-wheel plates, $LASH_5$.

The second group includes parameters that are required in the model input, but their value may be approximated within ± 25% error. These parameters are:

1- Tractor front suspension spring rates.

2- Equivalent trailer structure and fifth-wheel compliance, M5.

3- Lateral stiffness of the tires.

The third group includes parameters that must be accurately measured to determine an accurate value of the rollover threshold. These parameters are:

1- Tractor rear and trailer suspension spring rates.

2- Roll center heights, H_{Ri} .

3- Sprung mass C.G. heights, Z_{Si} .

4- Half Track widths, T_i .

5- Vertical stiffness of the tires, K_{Ti} .

It should be noted, however, that in the case of some parameters such as tire stiffness, C.G heights of the sprung mass, track width and roll center height, the parameters were varied for the three roll planes together. In other words, the effect of changing these parameters was not studied separately for each roll plane. Consequently, the effect seen is due to the change in the three parameters together. It should also be noted that the percent change for most of these parameters was in the range of 25% to 100%. Such change in the value of the parameters, although too wide a range in practice, should be kept in mind when evaluating the sensitivity of the parameters. For example a change of 50% of the baseline value of the vertical stiffness of the three tires results in a change of 3.3% in the rollover threshold. This change is small when considering the corresponding 50% change in the the tire stiffness. Thus the tire vertical stiffness should be considered as a parameter of secondary importance.

In all the sensitivity studies discussed above, the results were obtained by changing the data file and running SRM for each case. Thus, each parameter sensitivity result required one run of the program. In the next section, a mathematical sensitivity analysis is proposed. This method requires only one run of SRM in order to obtain a sensitivity matrix for each of the desired parameters. Once the sensitivity matrix for a certain parameter is obtained, the effect of changing that parameter on the response variables can be quickly calculated without further running SRM. Thus this proposed method avoids the need for repetitive running of SRM each time a parameter is changed.

4.5 Mathematical Sensitivity Analysis

In this section, the method used for sensitivity analysis will be explained and the equations derived starting with the 15 equations that describe the static roll model. The method will be applied to study the sensitivity of the more sensitive parameters and the results presented. Finally, the application and limitations of this method will be discussed.

4.5.1 Derivation of sensitivity equations

The 15 equations derived in section 4.3 describing the static equilibrium of a vehicle can be written in this form:

$$\left[A\right]\left\{\Delta x\right\} = \left\{B\right\} \tag{4.31}$$

where,

$\left[A\right]$ is a (16×16) coefficient matrix,

$\left\{\Delta x\right\} = \left\{\overline{\Delta x}\ ,\ \Delta\phi_{s3}\right\}$ and

$\left\{B\right\}$ is a (16×1) right hand side vector.

Taking the partial derivative of equation (4.31) with respect to the parameter P1, we get:

$$\left[\frac{\delta A}{\delta P1}\right]\left\{\Delta x\right\} + \left[A\right]\left\{\frac{\delta(\Delta x)}{\delta P1}\right\} = 0 \tag{4.32}$$

where P1 is any parameter that we choose to change.

In equation (4.32), $\left\{\frac{\delta(\Delta x)}{\delta P1}\right\}$ is the only unknown which can be obtained from:

$$\left\{\frac{\delta(\Delta x)}{\delta P1}\right\} = -\left[A\right]^{-1}\left[\frac{\delta A}{\delta P1}\right]\left\{\Delta x\right\} \tag{4.33}$$

This sensitivity vector, $\left\{\frac{\delta(\Delta x)}{\delta P1}\right\}$ is dependant on the value of the vector $\left\{\Delta x\right\}$, and the matrices $\left[A\right]$ and $\left[\frac{\delta A}{\delta P1}\right]$. The value of these vectors and matrices changes at different roll angles ϕ_{S3}. Thus, in order to calculate the sensitivity vector for certain vehicle parameters, the program SRM is run with the initial set of parameters $\left\{ P_i : P1, P2, P3 .. \right\}$ for each roll angle increment until rollover occurs. The matrices $\left[A\right]$ and $\left[\frac{\delta A}{\delta P_i}\right]$ are calculated at each roll angle increment for all the i parameters whose influence on the rollover threshold is to be estimated. The calculated values for $\left[A\right]$ and $\left[\frac{\delta A}{\delta P_i}\right]$ are used to calculate the sensitivity vectors $\left\{\frac{\delta(\Delta x)}{\delta P_i}\right\}$ which are then used to estimate the rollover threshold for the parametric variation considered. The elements of matrix $\left[A\right]$ are listed in Appendix B.

The matrix $\left[\frac{\delta A}{\delta P1}\right]$ will change depending on the parameter P1. This matrix is given below for the more sensitive parameters. If the matrix $\left[\frac{\delta A}{\delta P1}\right]$ is called $\left[D\right]$ then, For the parameter, ZS_3, the matrix $\begin{bmatrix}D\end{bmatrix}$ will be:

$$DZS_3(3,1) = (WAXL_3 - W_{U3})(-1+(\phi_{S3} - \phi_{U3})\phi_{U3}) - W_5$$

$$DZS_3(3,6) = (WAXL_3 - W_{U3})(1+(\phi_{S3} - \phi_{U3})a_y - (F_{31}+F_{32})$$

$$DZS_3(3,16) = (F_{31} + F_{32}) + W_5$$

For the parameter, S_2, the matrix $\begin{bmatrix}D\end{bmatrix}$ will be:

$$DS_2(2,3) = -2(K_{21} + K_{22})S_2$$

$$DS_2(2,5) = 2(K_{21} + K_{22})S_2$$

$$DS_2(2,8) = (K_{21} - K_{22})$$

$$DS_2(5,3) = 2(K_{21} + K_{22})S_2$$

$$DS_2(5,5) = -2(K_{21} + K_{22})S_2$$

$$DS_2(5,8) = -(K_{21} - K_{22})$$

$$DS_2(8,3) = -(K_{21} - K_{22})$$

$$DS_2(8,5) = (K_{21} - K_{22})$$

For the parameter, T_3, the matrix $\begin{bmatrix}D\end{bmatrix}$ will be:

$$DT_3(6,6) = -2(KT_{31}(T_3 + A_3) + KT_{32}T_3 + KT_{33}(T_3 + Y_3) + KT_{34}(A_3 + Y_3 + T_3))$$

$$DT_3(6,12) = KT_{31} - KT_{34} + KT_{32} - KT_{33}$$

$$DT_3(6,15) = -(KT_{33} + KT_{34})\phi_{U3}$$

$$DT_3(12,6) = -(KT_{31} + KT_{32} - KT_{32} - KT_{34})$$

For the parameter, A_3, the matrix $\left[D\right]$ will be:

$$DA_3(6,6) = -2(KT_{31}(T_3+A_3)+ KT_{34}(T_3+ Y_3+ A_3))$$
$$DA_3(6,15) = - KT_{34}\phi_{U3}$$
$$DA\ (6,12) = (KT_{31}- KT_{34})$$
$$DA_3(12,6) = - KT_{31}+ KT_{34}$$

Finally, the vector $\left\{\Delta x\right\}$ is nothing but the output resultant calculated from SRM at each roll angle increment $\Delta\phi_{S3}$.

4.5.2 Predicting new rollover threshold and rollover angle

Now that the sensitivity vector $\left\{\frac{\delta(\Delta x)}{\delta P1}\right\}$ is available, we can obtain the new value for any variable $\left\{\Delta x\right\}$ as follows. If the parameter P1 changes by the value ΔP1, then the corresponding change in the variable vector $\left\{\Delta x\right\}$ is:

$$\left\{d(\Delta x)\right\} = \left\{\frac{\delta(\Delta x)}{\delta P1}\right\} dP1 \tag{4.34}$$

The new variable matrix $\left\{\Delta x_{new}\right\}$ can be calculated using the following equation:

$$\left\{\Delta x_{new}\right\} = \left\{\Delta x_{old}\right\} + \left\{d(\Delta x)\right\} \tag{4.35}$$

Where $\left\{\Delta x_{old}\right\}$ is the value of the variables before the change dP1 in the parameter P1. This sequence of operation is repeated at every fixed small increment of roll angle. In this thesis, the roll angle increment is fixed at 0.2 degrees.

Now that the $\left\{\Delta x_{new}\right\}$ is available, we can estimate the new rollover angle and the corresponding lateral acceleration. This is done by checking the condition for rollover. For this purpose, the definition of rollover used is set to be initiated when the second and third axle tires lift-off the ground. This condition is reached when the tire deflection variables, $DELT_{21}$, $DELT_{22}$, $DELT_{31}$, $DELT_{32}$ are less than or equal to zero. In equation form, this is expressed as:

$$\begin{aligned} DELT_{21} &= -(T_2+A_2)\phi_{U2} + ZT_2 \leq 0 \\ DELT_{22} &= -T_2\phi_{U2} + ZT_2 \leq 0 \\ DELT_{31} &= -(T_3+A_3)\phi_{U3} + ZT_3 \leq 0 \\ DELT_{32} &= -T_3\phi_{U3} + ZT_3 \leq 0 \end{aligned} \qquad (4.36)$$

The above four conditions are evaluated at each roll angle increment. If the conditions are met, the vehicle is set to have rolled over. Not all of the above four conditions are met at the same roll angle value. The tire which requires the largest roll angle to lift-off is taken as the limiting condition. The angle at which rollover has just occurred is when this tire's deflection is just equal to zero. However, since the roll angle is incremented by .2

degrees, this value is most likely to jump from a positive to a negative value with just one incrementation. To calculate the exact roll angle, direct linear interpolation using the two tire deflection values is used.

The new rollover threshold can also be found by calculating the predicted lateral acceleration value at each roll angle increment. The maximum value of lateral acceleration calculated before rollover occurs is the new rollover threshold.

4.5.3 Results of Sensitivity Analysis

To demonstrate the effectiveness of the sensitivity analysis, a heavy vehicle with configuration and parameters as in [6] is selected. The parameter set for this vehicle is given in Appendix C. The rollover angle for this vehicle calculated from SRM is 10.4 degrees, with the corresponding lateral acceleration of .303 g and a rollover threshold of .301 g. Mathematical sensitivity analysis is performed on this vehicle and the results of the more sensitive parameters are discussed below.

Mathematical sensitivity analysis was carried out on the following parameters: The C.G height for the tractor front, tractor rear and semitrailer sprung mass, the spring spacing for the tractor front, tractor rear and semitrailer axles, the track width for the tractor front, tractor rear and semitrailer axles, the dual tire spacing for the tractor front, tractor rear and semitrailer tires,the roll center height of tractor front, tractor rear and semitrailer axles, fifth wheel height, fifth wheel stiffness, tractor frame roll stiffness, tractor frame C.G. height and the vertical, lateral and overturning stiffness for the tractor front, tractor rear and semitrailer tires.

The most sensitive parameters were found to be the semitrailer C.G. height, ZS_3, tractor rear half spring spacing, S_2, semitrailer half track width, T_3, and semitrailer dual tire spacing A_3. The rest of the parameters were found to have an effect of less than 2% on the rollover threshold for a variation of $\pm$ 15% in the parameter. These parameters in turn can be divided into two groups. The first is parameters that have some effect on the rollover threshold; however, that effect is less than 2%. The second group includes parameters that have less than .5% or no effect on the rollover threshold.

Parameters that belong to the first group include:

1. Tractor rear track width.
2. Trailer and tractor roll center heights.
3. Fifth wheel height.

Parameters that belong to the second group include:

1. Tractor front and tractor rear dual tire spacing.
2. Tractor front and tractor rear sprung mass C.G height.
3. Tractor frame C.G. height.
4. Tires vertical stiffness.
5. Tires lateral stiffness.
6. Tires overturning stiffness.

The sensitivity results of all the parameters studied were similar in magnitude and direction to those obtained by running SRM. However, the mathematical sensitivity analysis of the semitrailer half spring spacing showed an increase in the predicted rollover threshold value for an increase in the semitrailer half spring spacing. This increase was not obtained by running SRM with the new value. In [7], it is noted that the improvement in the rollover threshold due to increasing the semitrailer half spring spacing is related to the tractor roll stiffness. A low roll stiffness in the tractor suspension controls the rollover threshold result. In that case, increasing the roll stiffness at the trailer axles by increasing the spring spacing has little or no effect on improving the rollover threshold. This relationship between the tractor suspension roll stiffness and semitrailer spring spacing is not explicitly present in the sensitivity matrices and thus could not be taken into account in the mathematical sensitivity analysis.

Figures (4.9), (4.10), (4.11) and (4.12) show the predicted effect of changing the semitrailer sprung mass C.G. height vs. the actual effect obtained by running SRM. The numbers in brackets indicate the error in the predicted value. From Figures (4.9) and (4.10), it can be seen that decreasing the C.G. height reduces the rollover angle but increases the corresponding lateral acceleration at which rollover occurs. Figure (4.10) shows that a 20% decrease in the value of C.G. height results in about 40% increase in the lateral acceleration value at rollover. In both of these figures, it is clear that the predicted rollover angle and corresponding lateral acceleration are both overestimated. The error involved in predicting the new rollover angle and corresponding lateral acceleration increases as the change in C.G height increases. Form these figures, it can be seen that the new rollover angle and corresponding lateral acceleration can be predicted with less than 10% error for a change of up to 20% in the parameter.

Figure (4.11) shows the effect of changing the C.G. height on the rollover threshold. As seen in the figure, a 20% decrease in the C.G. height improves the rollover threshold by about 40%, while a 20% increase in C.G. height reduces the rollover threshold by about 25%. Here, the error involved in predicting the rollover threshold is related to the direction of change in the C.G. height. From this figure, it is clear that the error is larger for a positive change in the parameter. The error also increases as the change in the parameter increases. An increase of 5% results in 2.8% error, whereas an increase of 15% results in 11.5% error.

It is important to note at this point that this method of predicting the new rollover angle is limited to new rollover angles that are less than or equal to the nominal rollover angle (i.e. rollover angle corresponding to the baseline vehicle). This is because the variables, {Δx} and sensitivity tables required are known only up to that point. Consequently, this method cannot predict rollover angles that are higher than the nominal value. Similarly, the lateral acceleration values at each roll angle increment can be estimated only up to the nominal rollover angle. For the semitrailer C.G height, this is shown in Figure (4.12). This figure shows the predicted and actual lateral acceleration versus roll angle curves for a 10% increase in the semitrailer C.G height. The behaviour of the vehicle can be predicted up to the nominal rollover angle of 10.4° whereas actual rollover of the vehicle occurs at 13.1°.

The predicted effect of changing the tractor rear spring spacing vs. the actual effect obtained by running SRM, is shown in Figures (4.13), (4.14), (4.15) and (4.16). The effect of increasing the spring spacing on the rollover angle and the corresponding lateral acceleration is shown in Figures (4.13) and (4.14). From these two figures, it can be seen that increasing the spring spacing decreases the rollover angle and increases the corresponding lateral acceleration. A 20% increase in the spring spacing reduces the rollover angle by about 25% and increases the corresponding lateral acceleration by about 10%. The maximum error in predicting the new rollover angle is 11.2% for a 20% increase in the parameter. The corresponding error in predicting the lateral acceleration value at rollover is 4.8%. Thus the effect of increasing this parameter on the rollover angle and lateral acceleration can be predicted within reasonable error for changes up to 20%.

Figure (4.15) shows the effect of changing the tractor spring spacing on the rollover threshold. From the figure, it can be seen that increasing the spring spacing increases the rollover threshold. A 20% increase in the spring spacing results in an increase of around 10% in the rollover threshold. Looking at the predicted and actual curves in this figure, it is clear that the mathematical sensitivity analysis overestimates the effect of changing the parameter on the rollover threshold. The maximum error involved however, remains well below 10%.

Figure (4.16) gives the predicted and actual lateral acceleration versus roll angle curves for a decrease of 10%

in the spring spacing. As can be seen in the figure, the actual new rollover angle of 14.6° cannot be predicted, however, the predicted and actual lateral acceleration curves are quite close.

The predicted vs. actual effect of changing the semitrailer track width on the rollover angle and corresponding lateral acceleration is shown in Figures (4.17) and (4.18). From these two figures, it can be seen that increasing the half track width by about 15% results in decreasing the rollover angle by about 3% and increasing the corresponding lateral acceleration by about 15%. Figure (4.18) shows that the error in predicting the lateral acceleration at rollover increases rapidly with the increase in the change in parameter. An increase of 5% in T_3 results in 8.3% error whereas an increase of 15% in the same parameter results in 17.6% error. The error in predicting the rollover angle, however, is not as dependant on the magnitude of parameter change.

The effect of changing the semitrailer track width on the rollover threshold is shown in Figure (4.19). As shown in the figure, increasing the half track width by 15% increases the rollover threshold by about 13%, while decreasing the half track width by 15% decreases the rollover threshold by about 16%. From this figure, it can be seen that the magnitude of error is dependant on the direction of change in the parameter. A 15% increase in the parameter results in 17.6% error, whereas a 15% decrease in the same parameter results in only 7.2% error.

Figure (4.20) gives the predicted and actual lateral acceleration versus roll angle curves for a 10% decrease in the half track width. As can be seen form this figure, the actual rollover angle is 12.8° while the predicted curve goes up to the nominal rollover angle of 10.4°. However, the predicted and actual lateral acceleration values are very close as can be seen from the two curves.

The predicted vs. actual effect of changing the dual tire spacing of the trailer tires can be seen in Figures (4.21), (4.22), (4.23) and (4.24). Figures (4.21) and (4.22) show the effect of increasing the dual tire spacing on the rollover angle and the corresponding lateral acceleration. As can be seen from these figures an increase in the results in dual tire spacing reducing the angle at which the vehicle rolls over and increasing the corresponding lateral acceleration value. The error in predicting these two values increases as the the change in parameter increases, however, in both cases, the error remains less than 10% for up to 25% increase in parameter.

As can be seen in Figure (4.23), increasing the dual tire spacing on the semitrailer improves the rollover threshold. A 25% increase in the dual tire spacing improves the rollover threshold by about 10%, while a 25% decrease reduces the rollover threshold by about 5%. From this figure, it can be seen that the magnitude of error is dependant on the direction of change in the parameter. A change of +25% in the parameter results in a 7.7% error, whereas a-25% change in the parameter results in only 3.1 percent error. However in both cases, the error remains less than 10% for up to 25% change in the parameter.

Finally, Figure (4.24) shows the predicted and actual lateral acceleration versus roll angle curves for a 20% decrease in the dual tire spacing. As can be seen in the figure, the two curves are quite close.

4.5.4 Limitation

From the figures in the previous section, it is clear that there is some error involved in using the mathematical sensitivity analysis approach to predict the effect of changing a certain parameter on the vehicle's response. For the semitrailer C.G. height, the maximum error was 18% for a 20% change in the parameter. A change of 15% in the same parameter reduces the error to 11% and a change of 10% results in 6% error. Thus, a larger deviation from the nominal value of the parameter results in a larger error. A similar behaviour can be seen with the semitrailer track width. A change of 15% results in a large error of 17%

whereas a change of 5% results in a 7% error. Looking at the tractor rear spring spacing, the maximum error is 7.1% for a -20% change in the parameter. For the semitrailer dual tire spacing, the maximum error in predicting the rollover threshold is 8.3% for a 20% change in the parameter.

Another point to note is that direction of the parameter change can at times influence the amount of error involved. This is an indication of the assumption that is implied by using the mathematical sensitivity approach. In this method, it is assumed that the change in the variables is linearly related to the change in the parameter. Looking at the graphs of predicted and actual lateral acceleration values at rollover, it can immediately be seen that this is not actually the case. This assumption is a source of error that becomes more obvious with larger deviations from the nominal parameter value.

The application of the mathematical approach is to quickly, and within reasonable error, determine the new behaviour of a given vehicle when a certain parameter is changed. This method is intended to estimate of the new rollover threshold and roll angle within an acceptable range of error. If a more accurate result is required, the user should run the actual SRM program. The advantage of this method, however, is the availability of the sensitivity

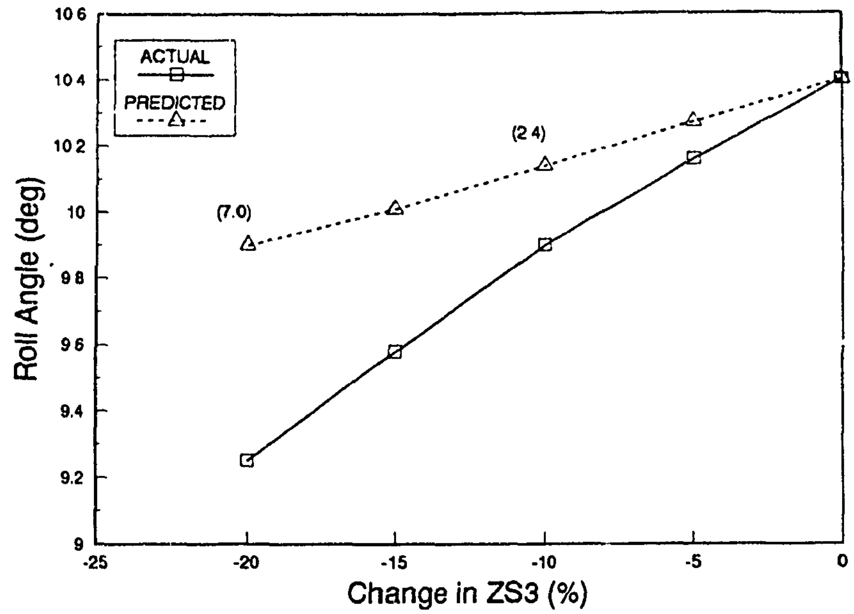


FIGURE 4.9 The Effect of Decreasing the Semitrailer C.G. Height on Semitrailer Roll Angle at Rollover

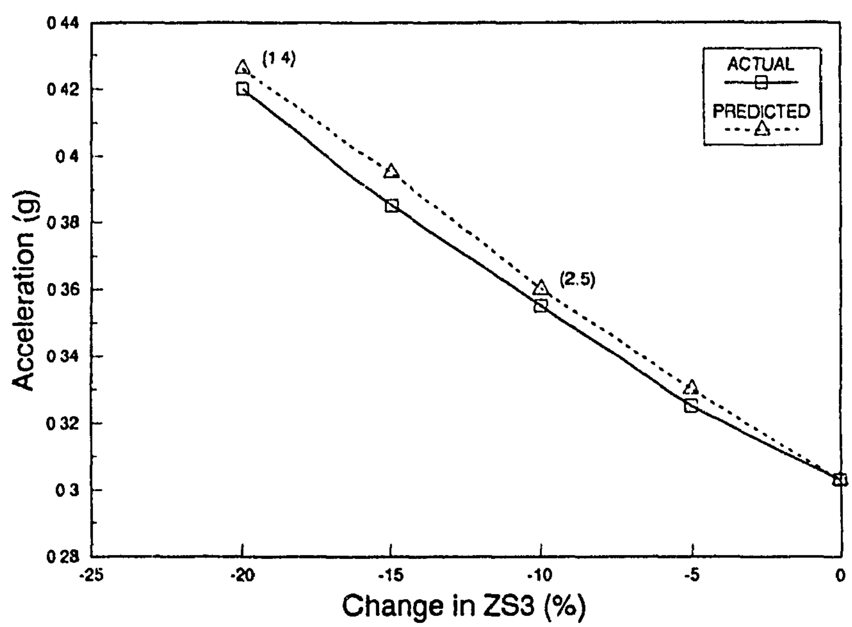


FIGURE 4.10 The Effect of Decreasing the Semitrailer C.G. Height on Lateral Acceleration at Rollover

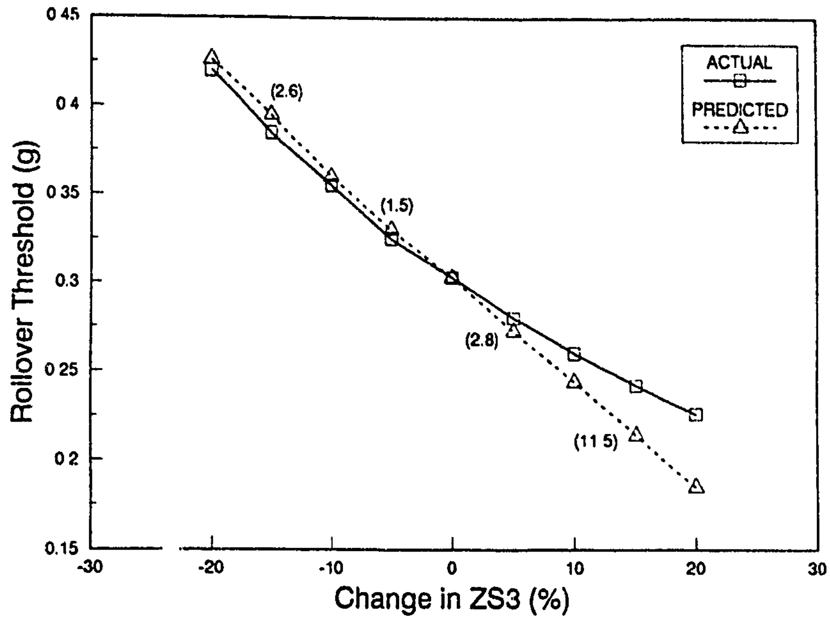


FIGURE 4.11 The Effect of Changing the Semitrailer C.G.Height on Rollover Threshold

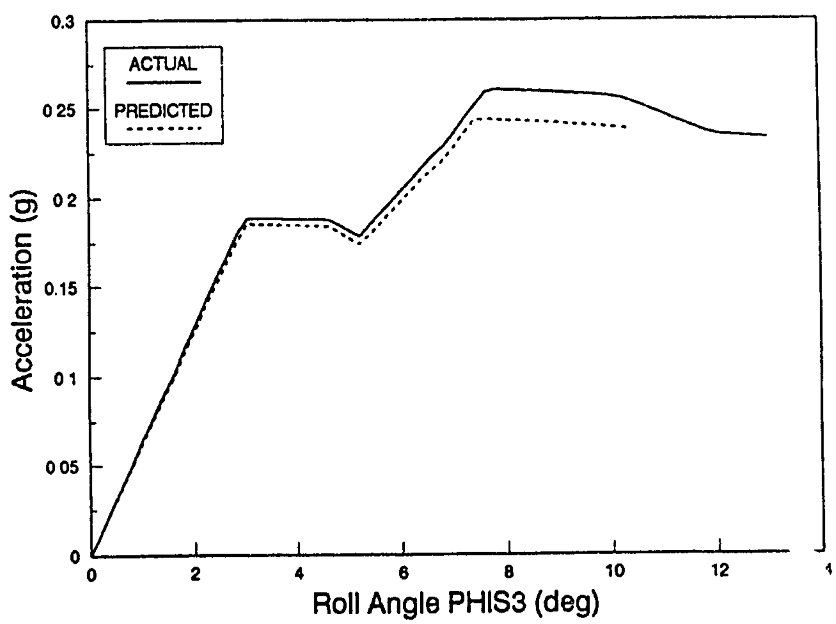


FIGURE 4.12 Lateral Acceleration vs. Semitrailer Roll Angle for a 10% Increase in Semitrailer C.G Height

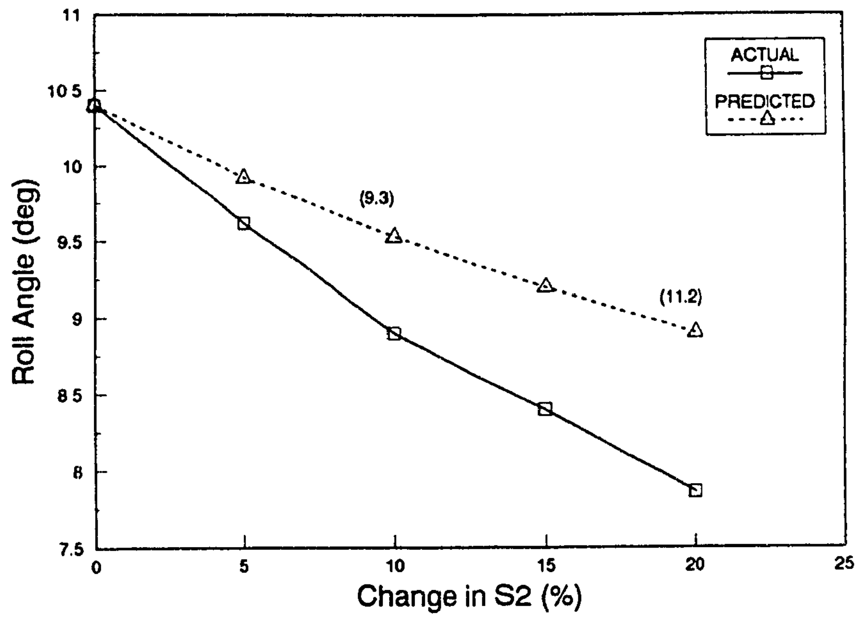


FIGURE 4.13 The Effect of Increasing the Tractor Rear Spring Spacing on Semitrailer Roll Angle at Rollover

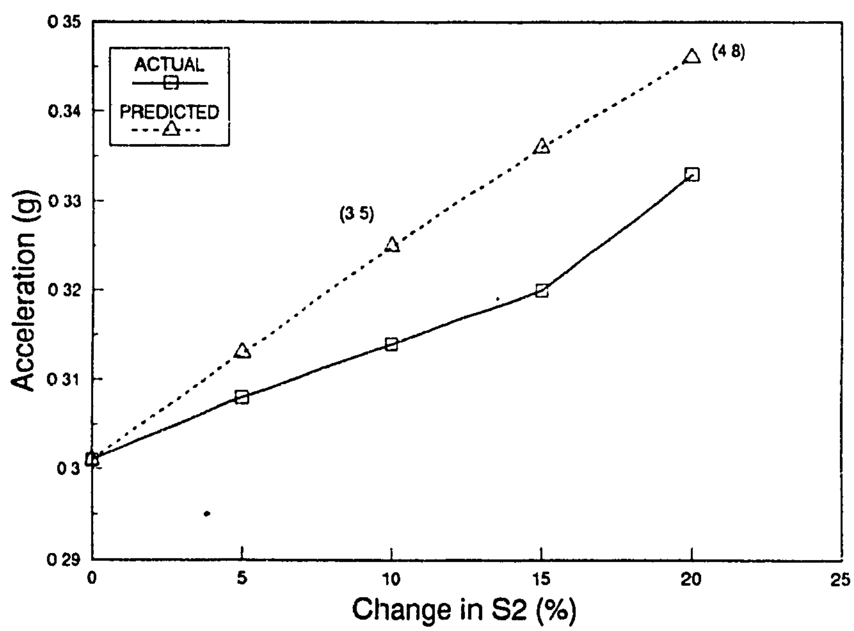


FIGURE 4.14 The Effect of Increasing the Tractor Rear Spring Spacing on Lateral Acceleration at Rollover

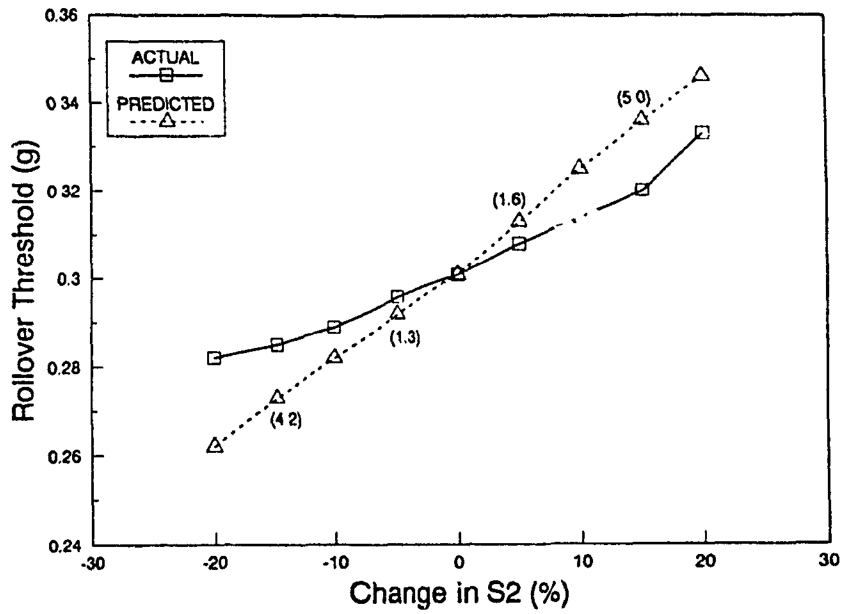


FIGURE 4.15 The Effect of Changing the Tractor Rear Spring Spacing on Rollover Threshold

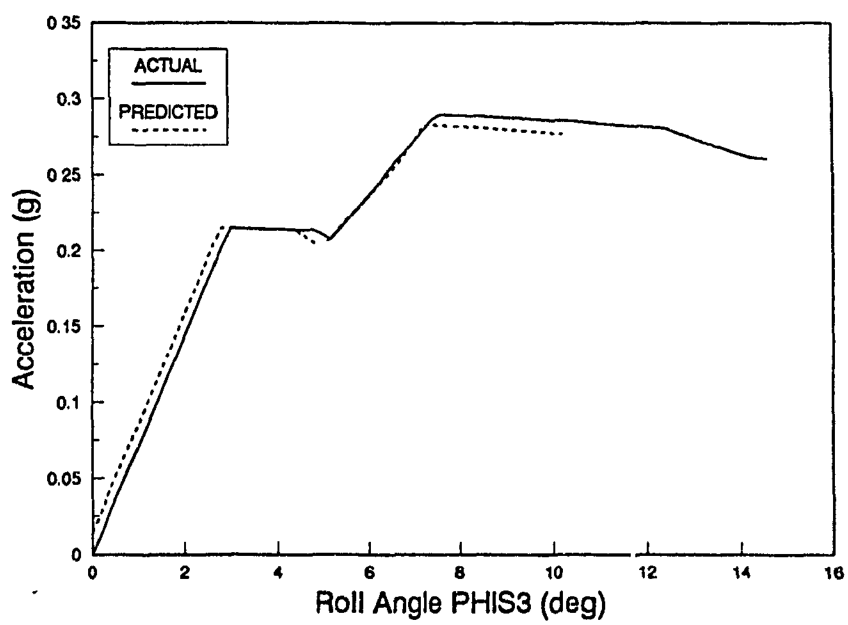


FIGURE 4.16 Lateral Acceleration vs. Semitrailer Roll Angle for a 10% Increase in Tractor Rear Spring spacing

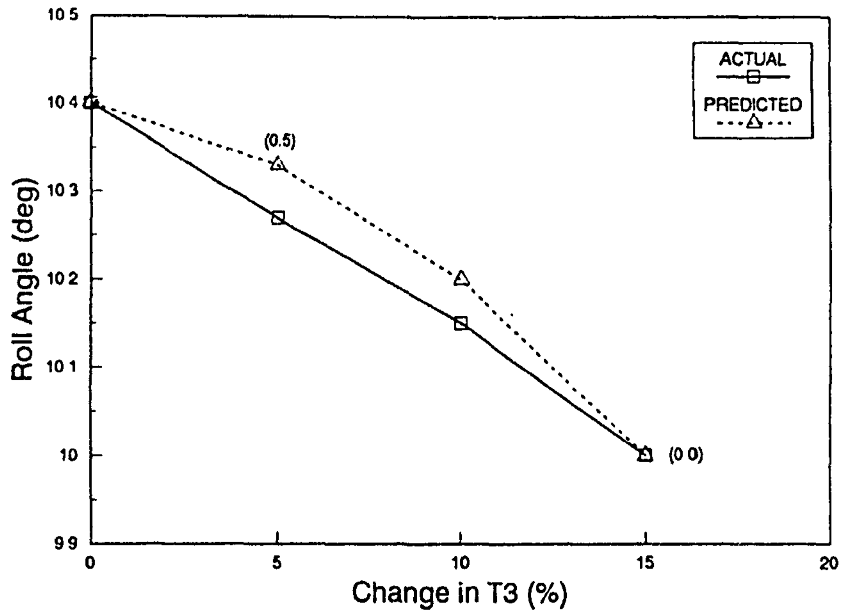


FIGURE 4.17 The Effect of Increasing the Semitrailer Half Track Width on Semitrailer Roll Angle at Rollover

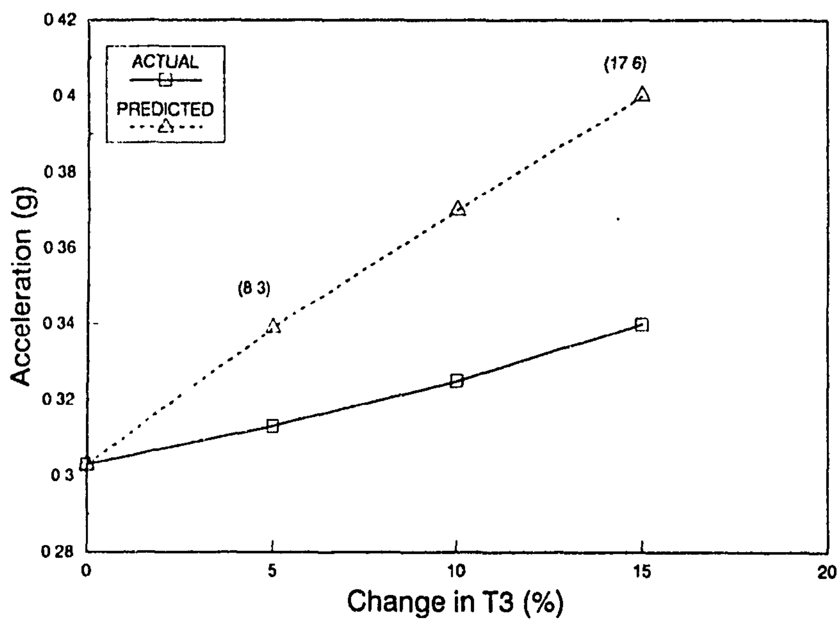


FIGURE 4.18 The Effect of Increasing the Semitrailer Half Track Width on Lateral Acceleration at Rollover

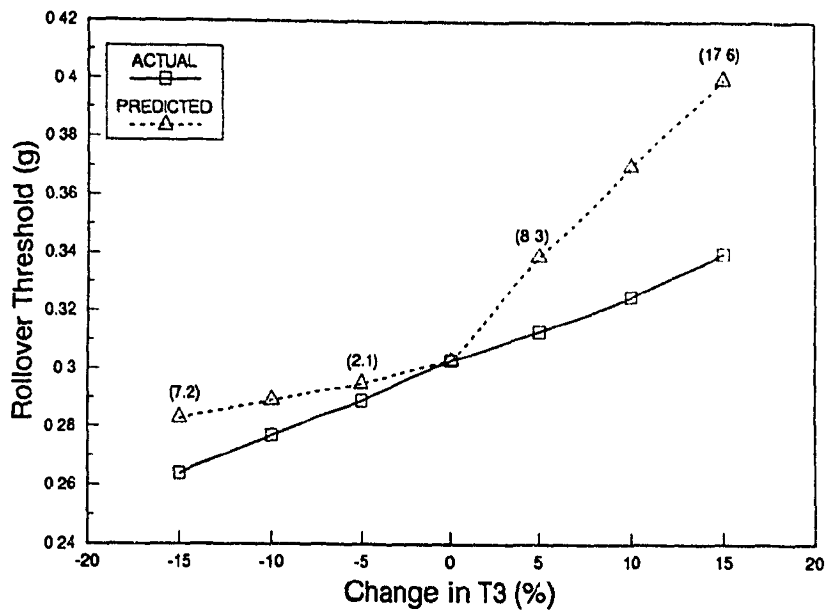


FIGURE 4.19 The Effect of Changing the Semitrailer Half Track Width on Rollover Threshold

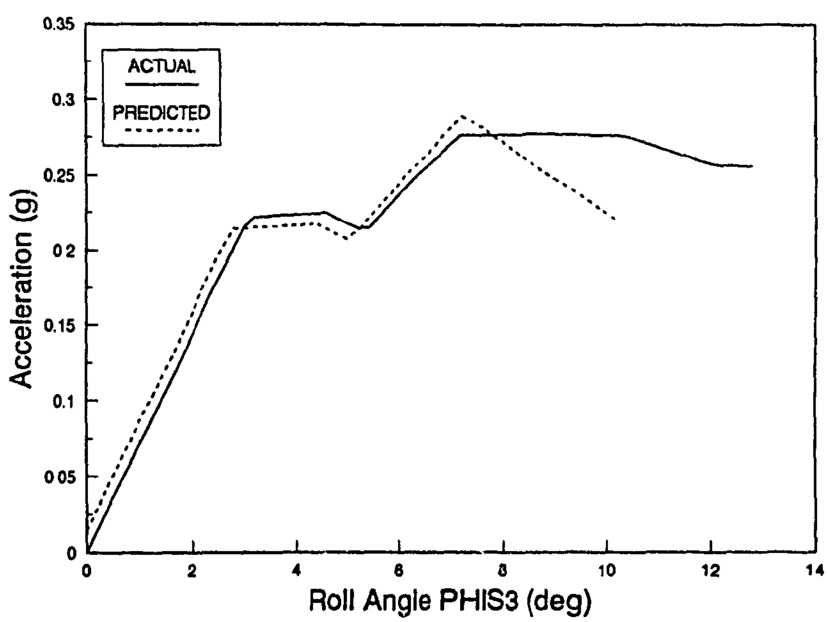


FIGURE 4.20: Lateral Acceleration vs. Semitrailer Roll Angle for a 10% Decrease in Semitrailer Half Track Width

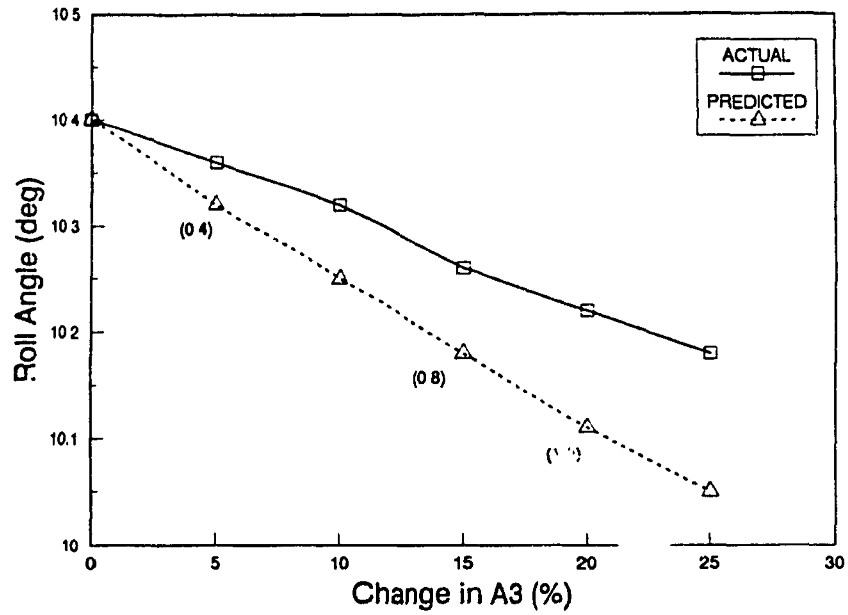


FIGURE 4.21: The Effect of Increasing the Semitrailer Dual Tire Spacing on Semitrailer Roll Angle at Rollover

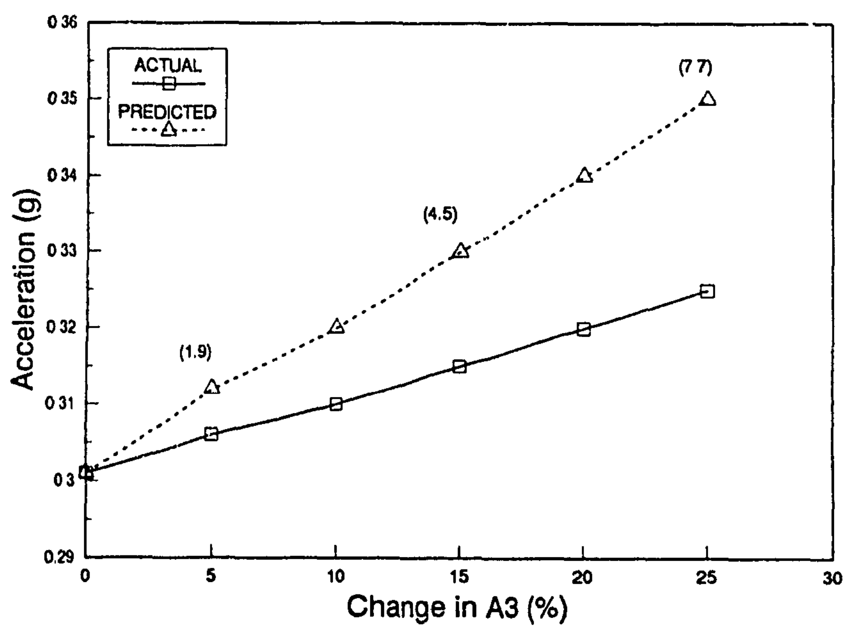


FIGURE 4.22: The Effect of Increasing the Semitrailer Dual Tire Spacing on Lateral Acceleration at Rollover

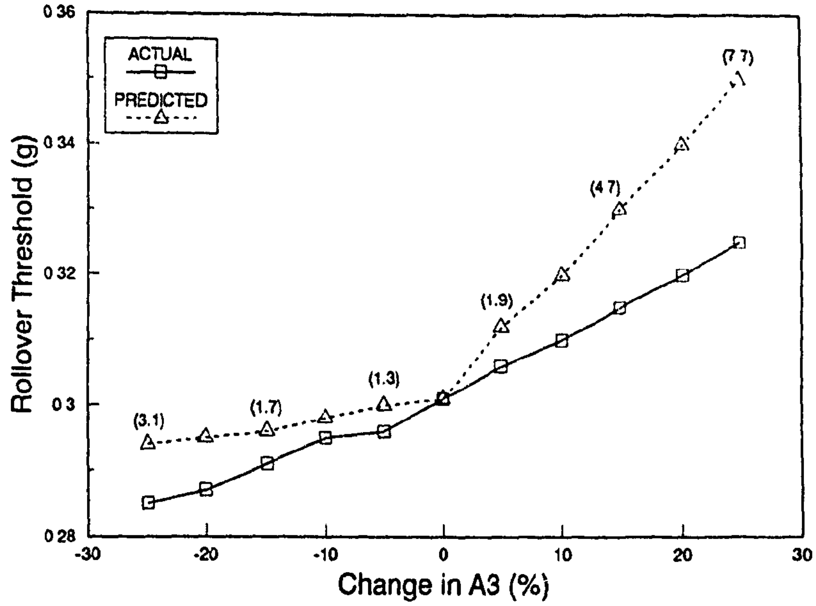


FIGURE 4.23: The Effect of Changing the Semitrailer Dual Tire Spacing on Rollover Threshold

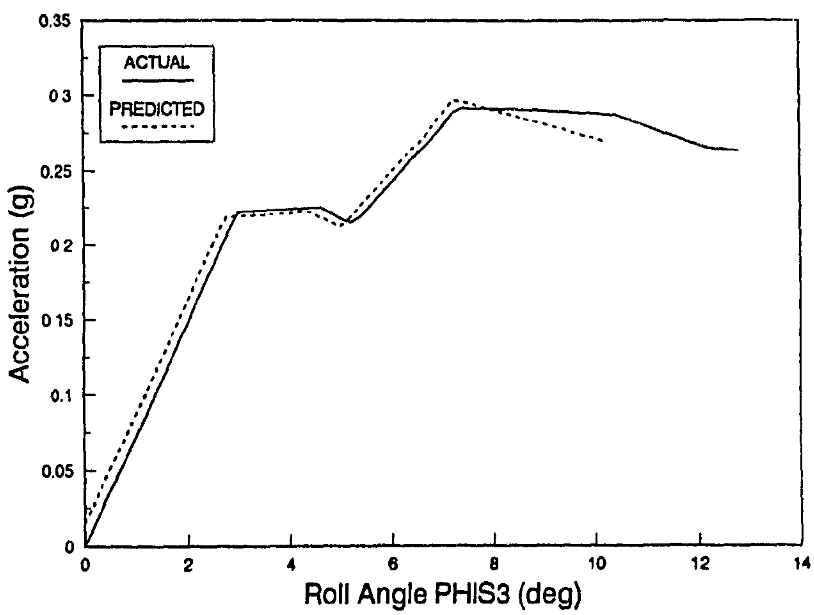


FIGURE 4.24: Lateral Acceleration vs. Semitrailer Roll Angle for a 20% Decrease in Semitrailer Dual Tire Spacing

matrix at any time to study the effect of changing a certain parameter. Thus if the vehicle configuration is fixed, and the user would like to know how changing a certain parameter will affect the stability of the vehicle, the program can quickly determine the new rollover threshold and roll angle.

4.6 Summary

In this chapter, a mathematical sensitivity analysis to study the effect of changing a certain vehicle parameter is presented. A static roll plane model describing the stability behaviour of a vehicle during steady turning is used to derive the necessary sensitivity equations and to evaluate the results of the mathematical sensitivity analysis. The results show that this method can be used as a quick estimate to predict the roll angle, lateral acceleration and rollover threshold within reasonable error.

CHAPTER 5

EVALUATION OF KNOWLEDGE-BASED SYSTEM: VELSAS

5.1 General

In Chapter 3, the development of the knowledge-based system: VELSAS is discussed. In this chapter, the overall structure of VELSAS is presented and evaluated. The evaluation will include the verification and validation of VELSAS, and a discussion of its advantages and limitations. The verification and validation of VELSAS requires many system runs of which few will be presented.

5.2 Overall Structure of KBS: VELSAS

It was mentioned in Chapter 2, that VP-EXPERT is a goal driven expert system tool. In this section, the sequence of the major goals is discussed and represented in Figure (5.1). At this stage, it is important to note two things.

The first point to note is that the goals discussed in this section do not include all the goals defined in the ACTIONS block of the expert system or the goals defined in the rule conclusions. This is because in most cases, attaining a certain major goal requires defining and attaining other sub-goals. For example to check if the load on the trailer axle group is legal, the expert system has to find the capacity of the tires and the maximum allowable load for that axle group as defined in the regulations.

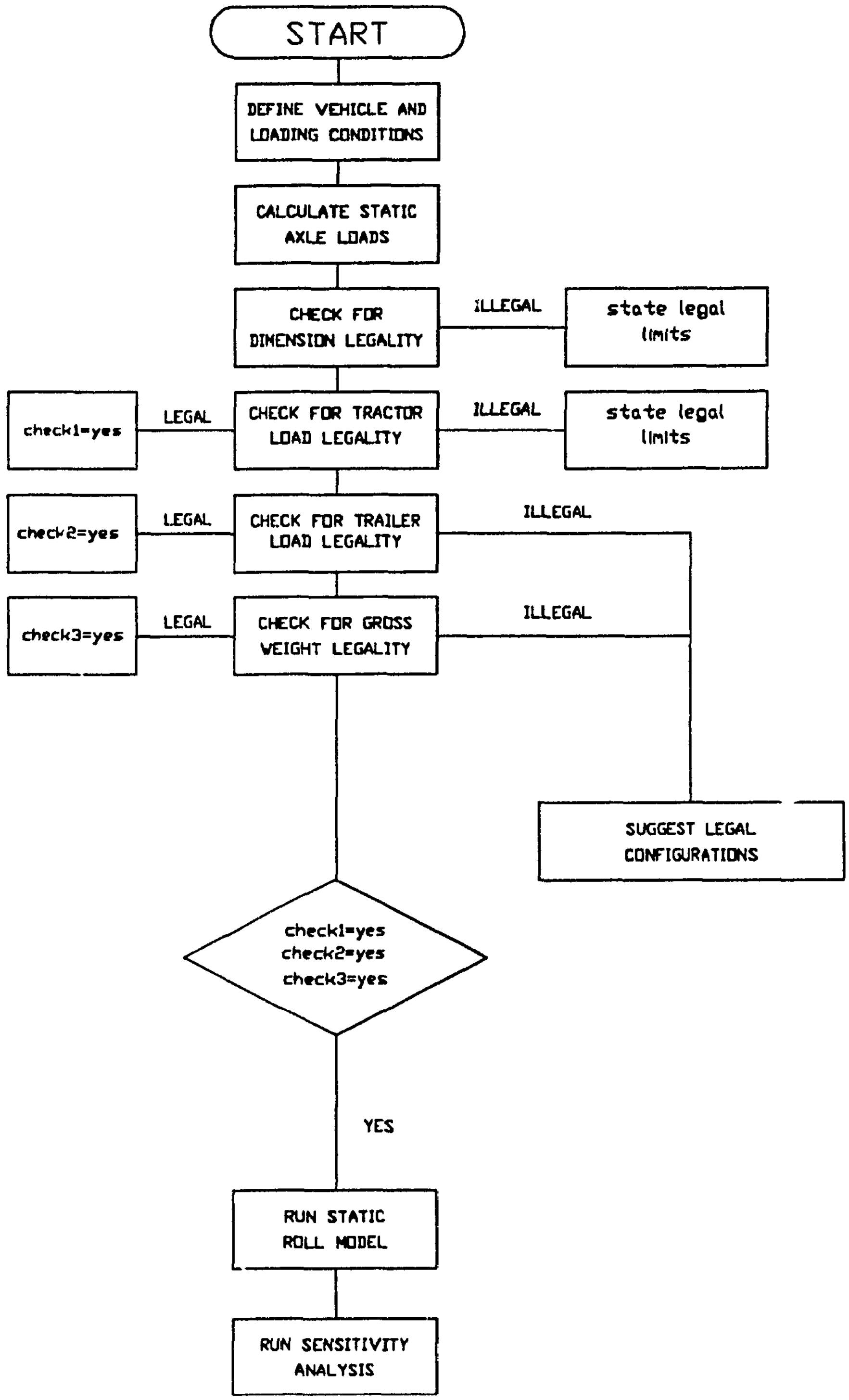


Figure 5.1 Sequence of Goals Followed by VELSAS

Then, the least of these two values is taken as the limiting load and compared to the actual load. Thus, the goal: ND trailer_legality, requires the two sub-goals: FIND trailercap and FIND trailer_max_load.

The second point to note, is that Figure (5.1) cannot be considered as a flowchart of the expert system. This is because a flowchart is supposed to represent the flow of a program. In the case of an expert system, the program is likely to take a different path every time it runs. This is because the path it takes depends on the user input as well as some of the results of rule conclusions. Thus, even though the goals defined in the ACTIONS block remain the same, the path taken by the expert system in attaining these goals is not usually the same.

Figure (5.1) describes the major goals of the expert system and their sequence. As can be seen from this figure, the vehicle is first defined, the axle loads calculated by calling the external program STATIC and the results transferred back to VP-EXPERT. Then, VP-EXPERT checks for the legality of the dimensions and axle loads. Checking for axle load legality is divided into three parts. The tractor front axle, tractor rear axle and trailer axle group. VP-EXPERT then checks for the vehicle gross weight legality. If the gross weight and axle loads are all legal, VP-EXPERT calls the external program SRM to calculate the rollover threshold and then allows the user to perform a sensitivity analysis on the vehicle by calling two other external programs. If the load on the semitrailer axle group or vehicle gross weight is found to be illegal, VP-EXPERT provides the user with some suggestions of trailer axle group modification that will result in a legal vehicle.

5.3 Verification and Validation of KBS: VELSAS

5.3.1 The verification and validation process

Verification and validation are very important in the evaluation and acceptance of any expert system. Although the terms verification and validation are often used interchangeably, there is a distinct difference between the two processes. The IEEE definitions are [22]:

.Verification: the process of determining whether or not the products of a given phase of software development meet all the requirements established during the previous phase.

.Validation : the process of evaluating software at the end of the development process to ensure compliance with software requirements.

These definitions are easily applicable for classical software, however, the life cycle and nature of expert system development suggest the need for a different approach to verification and validation.

No single approach or definition for the verification and validation of expert systems has been agreed upon. There have been many definitions and approaches to verification and validation. In [22], it is suggested that verification and validation can be distinguished according to the persons using them. The customer, is concerned with the validation process to insure that it does solve his problem. In this case, the customer is looking for the usability, competence, performance and reliability of the expert system. The builder on the other hand, is concerned with the verification process. The builder is looking for completeness, coherence, correctness, robustness as well as performance.

In [23], an incremental validation approach is proposed in which it is suggested that validation should address two problems: *Validation of the formalization* in order to determine whether a formalization correctly represents the actual user's intention and *validation of the user's intention* to determine whether the user's intention is correctly represented by the actual formalization.

In [24], Verification is defined as insuring that the expert system code *fully* and *exclusively* implements the required specifications, whereas validation is insuring that the code *correctly* implements the user requirements. According to this definition, verification is suggested to be, in many cases, a "paper" activity while validation is a "live" activity in which the software is tested.

Although there is no single approach to the verification and validation process, a knowledge of possible problems and error sources in expert systems can be helpful in verifying and validating expert systems. Some of these errors for rule based systems are given in [24]. The most trivial sort of error is typographical errors. Depending on the language, tool or shell used, this sort of error may either go unnoticed by the compiler to be detected only at runtime, or may be detected by the compiler and a warning message displayed to the builder. At other times, lack of attention in writing rules introduces errors such as a reverse in the direction of implication or omission of a part of the rule. Most of the time, the detection of such errors, requires running the expert system. Other errors are introduced when the system is being expanded to accommodate more requirements or incorporate more knowledge. The builder might modify most of the relevant rules but miss others. Some of the errors more specific to rule sets include redundancy in rules or inferences, conflict in initial and deducible facts and incompleteness due to missing rules, unconnected rules or missing facts.

With all these views and approaches to validation and verification, there is a lack of structured strategies or methodologies for either process. Despite this fact, the importance of checking the expert system performance and correctness is great. For the purpose of this expert system, the definitions of verification and validation given in [23] were used. Verification was sometimes limited to "paper" work, whereas at other times certain errors could only be detected at runtime. In many cases, it was found that the two were interrelated so that one was helpful in detecting errors that went unnoticed by the other.

.Looking at Figure (5.1), it can be seen that this expert system can actually be divided into smaller expert systems. This modular like structure of the expert system was helpful in the verification and validation process. Each part could be developed and tested alone and put aside while another part was being developed. Once these smaller expert systems were assembled into the final expert system, any new problems that occurred could most likely be attributed to the interaction between the different parts.

The method for validation and verification followed the method suggested in [23]. This defines the verification and validation as comprising of five tasks: defining the requirements, verifying the knowledge base and supporting software, preparing test cases, executing the test cases and evaluating the results. Each of these steps as applied to this expert system is discussed below.

Requirement Definition

The requirement definition for this expert system started with a general statement of purpose which was used to build the first prototype. As the expert system began to take shape, the requirements definition changed with the realization of the capabilities and possible applications . In most cases, requirements specification for expert systems is different than that for conventional computer programs. However, the structure of the knowledge base for this expert system, made it possible to define the the knowledge base requirements in the form of input/processing /output terms. Once the expert system was completed, the specified requirements were once more compared to the actual features of the system to insure that all the specified requirements were met.

Verification

The method used in verifying this expert system can be divided i ɔ two general categories: requirements tracing and engineering analysis.

Requirements tracing is done to insure that all the superior requirements are met by the subordinate ones and that there are no errors or omissions that might interfere in the passing from one development stage to the next. In general, the declarative nature of expert systems makes requirement tracing rather difficult. However, the modular like nature of this expert system made this process easier. For example, determining whether the load on the semitrailer axle group is legal was defined as a superior requirement specification. This requirement, generates two subordinate requirements: determining the maximum load allowed on the semitrailer axle group and the actual load on the semitrailer axle group. The requirement of determining the maximum load allowed on the semitrailer axle group in turn generates another two requirements, determining the maximum allowable load on the axle group as defined by Table 1 in the regulations (Appendix A) and determining the maximum allowable load on the semitrailer tires. These requirements in turn generate more subordinate requirements. This sort of structure which was seen throughout the expert system, made the requirement tracing quite practical and feasible.

Engineering analysis refers to insuring that the expert system will work as intended before it is expanded into the desired scale. In [23], different elements of engineering analysis are described. The elements proposed are presented and those that were found to be applicable are discussed with reference to the expert system at hand.

The first element is to consider is how critical the application of the expert system is. This is a study of how the failure of the expert system affects the purpose for which it was built. If the expert system is just a part of a larger software, then it is important to consider how the failure of the expert system affects the other components and overall performance of the software. For the expert system at hand, a correct performance of this system is quite critical. This is because of two reasons. The first reason is that this expert system is concerned with government regulations, and a simple error can very likely result in declaring an illegal vehicle to be legal or vice versa. The second reason is that the expert system, with the exception of the external programs it calls, makes for the major part of the software. Thus a correct performance of the expert system is critical for providing correct answers.

The second element in the engineering analysis is the sensitivity of the expert system to minor variations in the inputs, particularly around operating limits, if there are any. Once more, the nature of the application of this expert system necessitates the accuracy and correctness of the information provided. Failure to do so, may result in one or more incorrect conclusions given by the expert system. For example an inaccurate axle position, or load value may result in an incorrect conclusion about the legality of the vehicle.

The third element in the engineering analysis is the efficiency of the expert system or the ability of the system to perform the required job within the given time and resources. In the case of the expert system at hand, the system can be considered as quite efficient in checking all the relevant regulations and especially in suggesting legal configurations.

The fourth element to be considered is the maintainability of the expert system. The nature of expert systems is such that they require expansion or modification to accommodate new requirements or incorporate new knowledge. For this reason, maintainability is of great importance in expert systems. Accordingly, great care was taken when building this expert system to insure that the rule base is easy to read and that meaningful variable names were used whenever possible.

The fifth element to be considered is the interaction analysis, or the ability of the interacting components of the expert system to produce the required results. In the case of the expert system at hand, this may refer to the interaction between the external programs and VP-EXPERT as well as the interaction between the two knowledge bases. A correct interaction can be verified very easily by insuring that the variable values passed between these different parts are the correct values and that the variable names are the same. As mentioned before, the structure of this expert system is such that it can be divided into a number of smaller modules. Thus correct interaction may also refer to obtaining the intended behaviour resulting from the interaction of these smaller expert systems.

The sixth element to look at is truth analysis. Truth analysis insures that the content of the knowledge base is correct. For example, a rule that defines the maximum allowable load for an axle group under certain loading conditions should be consistent with the government regulations. This can be done by comparing the rules with the published regulations so that rules are representative of the regulations.

Another suggested element of engineering analysis is the uncertainty analysis. This analysis is required when the expert system employs uncertainty factors. However, as described in chapter 2, the expert system at hand uses a certainty factor of 100 at all times. This is because the laws and regulations used to build it have no measure of uncertainty.

Finally, another point, not suggested in [23] is completeness analysis. This analysis is important in insuring that no relevant or important information went unrepresented in the knowledge base. This can be done by checking that each relevant regulation is represented by one or more rules as required. Taking the semitrailer axle load example again, this analysis would insure that every possible combination of axle group type, axle spacing, loading conditions and year of model that is present in the regulations is represented in the rule base.

Test Case Preparation

The selection of test cases should be done with the following points in mind:

-Every requirement should be tested. This is to insure that all the requirements have been met. In most cases, if one or more requirement is not met, it is possible to find a test case that will point that out.

-Every rule and possible conclusion should be tested. This requirement usually requires a close study of the rule base in order to determine how to reach a certain conclusion. In the case of the expert system at hand this was found to be impractical since it requires testing a tremendous combination of inputs. Consequently, the cases selected were those that tested representative rules and rules where error was more likely to occur.

Testing an intelligent choice of combinations. This is closely related to the above requirement. Again not all combinations can be tested, however, the combinations that are, should be well representative of the other combinations that are not tested.

Test Execution

Once the test cases are chosen according to the above criteria, the test cases are executed and their results recorded. The results of these tests are later used in the evaluation of the expert system. At other times, the results may reveal one or more errors that can be immediately corrected before further testing is done.

Validation

In most expert systems, validation is the most controversial part of the verification and validation process. One cause of this problem is that in many cases, there may be no single best answer. Instead there may be a set of acceptable answers which may not all be provided by the expert system. Another cause could be the human factor involved in the evaluation process which may give rise to problems such as prejudice, inconsistency or differences in opinion. The use of uncertainty factors presents another difficulty in the evaluation process. With the exception of the first problem, the problems discussed above were not encountered in the evaluation of this expert system. Again, this is largely due to the nature of knowledge represented and the absolute certainty of the regulations.

Some of points to be checked when evaluating the expert system are:

-Whether the obtained results are the same as, or equivalent to, the expected ones.

-Whether the explanation and justification provided by the expert system is satisfactory.

-Whether the inference process followed by the expert system is sufficiently complete and robust. As well whether the knowledge employed is of such quality and quantity to encourage customer confidence in the expert system.

At this stage it is important to note that the points just mentioned in the verification and validation requirements are by no means exhaustive. However, they do provide a good outline to go by in the evaluation of this expert system. What follows is a presentation of a few test cases and a validation of their results.

5.3.2 Test cases for KBS: VELSAS and results

The test cases presented are such that they represent a few different possible results of the expert system. A printout of the VP-EXPERT consultation screen is given for each of the test cases presented.

CASE 1

Semitrailer Data

Number of axles : 1

Overall length: 14.63 m.

Kingpin offset: .91 m.

Wheelbase: 12.0 m.

Distance from empty semitrailer C.G to kingpin: 8.0 m.

Distance from payload C.G to kingpin: 8.0 m.

Weight of empty semitrailer: 6200 kg.

Weight of payload: 30000 kg.

Tractor Data

Wheelbase: 4.83 m.

Fifth-wheel offset: 0.41 m.

Tandem spread: 1.52 m.

Distance form tractor C.G. to tractor front axle: 1.4 m.

Weight of Tractor: 8200 kg.

At the beginning of its run, VP-EXPERT calls the external program static which calculates the axle loads and writes to a file to be read by VP-EXPERT. The consultation windows for this vehicle are given in the following pages.

```
THE LOAD ON THE TRACTOR FRONT AXLE IS 6847.48 kg.
THE LOAD ON THE TRACTOR REAR AXLE is 13419.19 kg.
THE LOAD ON THE FIFTH WHEEL IS 12066.67 kg.
THE LOAD ON THE TRAILER AXLES IS 24133.34 kg.

Now checking for vehicle dimensions legality

Is your vehicle model older than 1992?
 yes ◂                    no

THE LENGTH OF THE SEMITRAILER IS LEGAL

what is the total length of your vehicle in (m)?
 18

TOTAL VEHICLE LENGTH IS LEGAL

what is the height, including cargo, of the semitrailer in (m)?
 4.0█
```

Enter to select   ? & Enter for Unknown   /Q to quit

```
 4.0

THE VEHICLE HEIGHT IS LEGAL

what is the width, including cargo, of the semitrailer in (m)?
 2.44

THE VEHICLE WIDTH IS LEGAL

Now looking for legality of tractor front and rear axle loads
What is the tractor front axle type?
 single ◂                 tandem                    multiple

what is the capacity of the tractor front axle in (kg)?
 7000

what is the tractor front tire load rating in (kg)?
 3000

what is the width of the tires on the tractor rear axle in (mm)?
 279.4█
```

Enter to select   ? & Enter for Unknown   /Q to quit

```
 279.4

what is the tractor rear tire load rating in (kg)?
 2800

What is the tractor rear axle type?
 single                     tandem ◄


What is the loading condition?
 timber no snow            normal no snow ◄          either snow thawing

THE LOAD ON TRACTOR FRONT AXLE IS ILLEGAL.
THE ACTUAL LOAD OF 6847.48 EXCEEDS THE LEGAL LIMIT OF 6000 kg.
THE MAXIMUM LOAD ALLOWED ON TRACTOR REAR AXLE IS 18000 kg.
THE LOAD ON TRACTOR REAR AXLE IS LEGAL
YOUR TRACTOR IS ILLEGAL. PLESAE PRESS RETURN TO CONTINUE WITH CONSULTATION
Now looking for maximum load allowed on trailer axles

what is the width of the tires on the trailer in (mm)?
 279.4█
```

```
Enter to select    ? & Enter for Unknown    /Q to quit
```

```

what is the width of the tires on the trailer in (mm)?
 279.4

what is the trailer tire load rating in (kg)?
 2800

What is the trailer axle type?
 single                    tandem ◄                  tridem or equivalent
 single and tandem         tandem and single         four or more
 single and tridem         two or more               two single axles
 three or more single      three or more             single donkey

THE MAXIMUM LOAD ALLOWED ON TRAILER AXLES  ACCORDING
TO TABLE 1 IN THE REGULATIONS IS 20000 kg.

Now looking for gross weight legality for this vehicle

The gross weight as calculated is 44400.010000.
Do you want to enter exact gross weight?
 yes                       no ◄
```

```
↑ ↓ ↕    Enter to select   END to complete    /Q to Quit    ? for Unknown
```

```
What is the trailer axle type?
 single                   tandem ◂                 tridem or equivalent
 single and tandem        tandem and single        four or more
 single and tridem        two or more              two single axles
 three or more single     three or more            single donkey

THE MAXIMUM LOAD ALLOWED ON TRAILER AXLES  ACCORDING
TO TABLE 1 IN THE REGULATIONS IS 20000 kg.

Now looking for gross weight legality for this vehicle

The gross weight as calculated is 44400.010000.
Do you want to enter exact gross weight?
 yes                      no ◂

what is the distance between the frontmost trailer axle and the rearmost axle
of the tractor in (m)?
 9.34

YOUR VEHICLE GROSS WEIGHT IS ILLEGAL. IT EXCEEDS THE CAPACITY OF 44000 kg.
PLEASE PRESS RETURN.
```

```
THE LOAD ON TRAILER AXLE EXCEEDS LEGAL LIMIT OF 20000 kg.
   SPECIFIED BY TABLE 1 IN THE REGULATIONS
THE LOAD ON TRAILER AXLE EXCEEDS THE TIRES CAPACITY OF 22400 kg.
THE TRAILER IS ILLEGAL.

YOU HAVE TO CHANGE TRAILER AXLE CONFIGURATION.
PLEASE PRESS RETURN TO RESUME WITH CONSULTATION
CURRENTLY LOOKING FOR POSSIBLE SOLUTIONS. PLEASE WAIT.
the total number of suggestions available is 4, how
many would you like to see?
 4

single and tandem  WITH A SPACING
   OF 3.6 m. placed at 9.030002 m. from tractor rear axle.
tridem or equivalent  WITH A SPACING
   OF 3.6 m. placed at 10.830002 m. from tractor rear axle.
single and tridem  WITH A SPACING
   OF 5.4 m. placed at 8.130002 m. from tractor rear axle.
four or more  WITH A SPACING
   OF 3.6 m. placed at 10.830002 m. from tractor rear axle.
```

CASE 2

Semitrailer Data

Number of axles: 2

Overall length: 14.63 m.

Kingpin offset: .91 m.

Distance from trailer rearmost axle to kingpin: 13.5 m.

Distance from trailer frontmost axle to kingpin: 10.5 m.

Distance from empty semitrailer C.G to kingpin: 8.2 m.

Distance from payload C.G to kingpin: 8.0 m.

Weight of empty semitrailer: 6200 kg.

Weight of payload: 23000 kg.

Tractor Data

Wheelbase: 4.83 m.

Fifth-wheel offset: 0.20 m.

Tandem spread: 1.52 m.

Distance form tractor C.G. to tractor front axle: 1.4 m.

Weight of Tractor: 8200 kg.

The results of the consultation for this vehicle are given in the following pages.

```
THE LOAD ON THE TRACTOR FRONT AXLE IS 5306.46 kg.
THE LOAD ON THE TRACTOR REAR AXLE is 12478.92 kg.
THE LOAD ON THE FIFTH WHEEL IS 9585.38 kg.
THE LOAD ON THE TRAILER AXLES IS 19614.62 kg.

Now checking for vehicle dimensions legality

Is your vehicle model older than 1992?
 yes ◂                        no

THE LENGTH OF THE SEMITRAILER IS LEGAL

what is the total length of your vehicle in (m)?
 18

TOTAL VEHICLE LENGTH IS LEGAL
what is the height, including cargo, of the semitrailer in (m)?
 4

THE VEHICLE HEIGHT IS LEGAL
```

```
what is the width, including cargo, of the semitrailer in (m)?
 2.44

THE VEHICLE WIDTH IS LEGAL

Now looking for legality of tractor front and rear axle loads
What is the tractor front axle type?
 single ◂                 tandem                   multiple

what is the capacity of the tractor front axle in (kg)?
 7000

what is the tractor front tire load rating in (kg)?
 3000

what is the width of the tires on the tractor rear axle in (mm)?
 279.4

what is the tractor rear tire load rating in (kg)?
 2800█
```

Enter to select   ? & Enter for Unknown   /Q to quit

```
 2800

What is the tractor rear axle type?
 single                     tandem ◂


What is the loading condition?
 timber no snow             normal no snow           either snow thawing ◂

Will you be travelling only on autoroutes?
 yes                        no ◂

THE MAXIMUM LOAD ALLOWED ON TRACTOR FRONT AXLE IS 6000 kg.
THE LOAD ON TRACTOR FRONT AXLE IS LEGAL
THE MAXIMUM LOAD ALLOWED ON TRACTOR REAR AXLE IS 15000 kg.
THE LOAD ON TRACTOR REAR AXLE IS LEGAL
YOUR TRACTOR IS LEGAL. PLESAE PRESS RETURN TO CONTINUE WITH CONSULTATION
Now looking for maximum load allowed on trailer axles

what is the width of the tires on the trailer in (mm)?
 279.4█
```

Enter to select   ? & Enter for Unknown   /Q to quit

```
 2800

What is the tractor rear axle type?
 single                     tandem ◂


What is the loading condition?
 timber no snow             normal no snow           either snow thawing ◂

Will you be travelling only on autoroutes?
 yes                        no ◂

THE MAXIMUM LOAD ALLOWED ON TRACTOR FRONT AXLE IS 5600 kg.
THE LOAD ON TRACTOR FRONT AXLE IS LEGAL
THE MAXIMUM LOAD ALLOWED ON TRACTOR REAR AXLE IS 15000 kg.
THE LOAD ON TRACTOR REAR AXLE IS LEGAL
YOUR TRACTOR IS LEGAL. PLESAE PRESS RETURN TO CONTINUE WITH CONSULTATION
Now looking for maximum load allowed on trailer axles

what is the width of the tires on the trailer in (mm)?
 279.4█
```

Enter to select   ? & Enter for Unknown   /Q to quit

```
what is the trailer tire load rating in (kg)?
 2800

What is the trailer axle type?
 single                   tandem                   tridem or equivalent
 single and tandem ◄      tandem and single        four or more
 single and tridem        two or more              two single axles
 three or more single     three or more            single donkey

THE MAXIMUM LOAD ALLOWED ON TRAILER AXLES  ACCORDING
TO TABLE 1 IN THE REGULATIONS IS 20000 kg.

Now looking for gross weight legality for this vehicle

The gross weight as calculated is 37400.
Do you want to enter exact gross weight?
 yes ◄                    no

what is the gross weight of the vehicle in (kg)?
 37500█

what is the distance between the frontmost trailer axle and the rearmost axle
of the tractor in (m)?
 9.55

YOUR VEHICLE GROSS WEIGHT IS WITHIN LEGAL LIMITS. PLEASE PRESS RETURN.
```

```
THE LOAD ON TRAILER AXLE IS LEGAL.
THE LOAD ON TRAILER TIRES IS LEGAL.
THE TRAILER IS LEGAL.
```

```
1Help     2Go       3WhatIf   4Variable 5Rule     6Set      7Edit     8Quit
1Help 2How? 3Why? 4Slow 5Fast 6Quit
```

CASE 3

Semitrailer Data

Number of axles: 2

Overall length: 14.63 m.

Kingpin offset: .91 m.

Distance from trailer rearmost axle to kingpin: 12.0 m.

Distance from trailer frontmost axle to kingpin: 10.5 m.

Distance from empty semitrailer C.G to kingpin: 8.0 m.

Distance from payload C.G to kingpin: 7.0 m.

Weight of empty semitrailer: 6000 kg.

Weight of payload: 20000 kg.

Tractor Data

Wheelbase: 4.83 m.

Fifth-wheel offset: 0.30 m.

Tandem spread: 1.52 m.

Distance form tractor C.G. to tractor front axle: 1.4 m.

Weight of Tractor: 8200 kg.

The results of the consultation for this vehicle are given in the following pages.

```
THE LOAD ON THE TRACTOR FRONT AXLE IS 6399.66 kg.
THE LOAD ON THE TRACTOR REAR AXLE is 11081.58 kg.
THE LOAD ON THE FIFTH WHEEL IS 9281.24 kg.
THE LOAD ON THE TRAILER AXLES IS 16718.76 kg.

Now checking for vehicle dimensions legality

Is your vehicle model older than 1992?
 yes                       no ◂

What is the trailer axle type?
 single                    tandem                    tridem or equivalent
 single and tandem         tandem and single         four or more
 single and tridem         two or more               two single axles ◂
 three or more single      three or more             single donkey

THE LENGTH OF THE SEMITRAILER IS LEGAL

what is the total length of your vehicle in (m)?
 18█
```

Enter to select ? & Enter for Unknown /Q to quit

```
TOTAL VEHICLE LENGTH IS LEGAL
what is the height, including cargo, of the semitrailer in (m)?
 4

THE VEHICLE HEIGHT IS LEGAL

what is the width, including cargo, of the semitrailer in (m)?
 2.7

THE VEHICLE WIDTH IS ILLEGAL, THE MAXIMUM ALLOWABLE WIDTH IS 2.6 m.

Now looking for legality of tractor front and rear axle loads
What is the tractor front axle type?
 single ◂                  tandem                    multiple

what is the capacity of the tractor front axle in (kg)?
 7000

what is the tractor front tire load rating in (kg)?
 █
```

Enter to select ? & Enter for Unknown /Q to quit

```
what is the tractor front tire load rating in (kg)?
 3000

what is the width of the tires on the tractor rear axle in (mm)?
 279.4

what is the tractor rear tire load rating in (kg)?
 3000

What is the tractor rear axle type?
 single                   tandem ◂


What is the loading condition?
 timber no snow ◂         normal no snow          either snow thawing

THE LOAD ON TRACTOR FRONT AXLE IS ILLEGAL.
THE ACTUAL LOAD OF 6399.66 EXCEEDS THE LEGAL LIMIT OF 6000 kg.
THE MAXIMUM LOAD ALLOWED ON TRACTOR REAR AXLE IS 20000 kg.
THE LOAD ON TRACTOR REAR AXLE IS LEGAL
YOUR TRACTOR IS ILLEGAL. PLESAE PRESS RETURN TO CONTINUE WITH CONSULTATION
```

```
THE LOAD ON TRACTOR FRONT AXLE IS ILLEGAL.
THE ACTUAL LOAD OF 6399.66 EXCEEDS THE LEGAL LIMIT OF 6000 kg.
THE MAXIMUM LOAD ALLOWED ON TRACTOR REAR AXLE IS 20000 kg.
THE LOAD ON TRACTOR REAR AXLE IS LEGAL
YOUR TRACTOR IS ILLEGAL. PLESAE PRESS RETURN TO CONTINUE WITH CONSULTATION
Now looking for maximum load allowed on trailer axles

what is the width of the tires on the trailer in (mm)?
 279.4

what is the trailer tire load rating in (kg)?
 3000

THE MAXIMUM LOAD ALLOWED ON TRAILER AXLES  ACCORDING
TO TABLE 1 IN THE REGULATIONS IS 13500 kg.

Now looking for gross weight legality for this vehicle

The gross weight as calculated is 34200.
Do you want to enter exact gross weight?
 yes                      no ◂
↑ ↓ ↕    Enter to select    END to complete    /Q to Quit    ? for Unknown
```

```
THE LOAD ON TRAILER AXLE EXCEEDS LEGAL LIMIT OF 13500 kg.
   SPECIFIED BY TABLE 1 IN THE REGULATIONS
THE LOAD ON TRAILER TIRES IS LEGAL.
THE TRAILER IS ILLEGAL.

YOU HAVE TO CHANGE TRAILER AXLE CONFIGURATION.
PLEASE PRESS RETURN TO RESUME WITH CONSULTATION
CURRENTLY LOOKING FOR POSSIBLE SOLUTIONS. PLEASE WAIT.
the total number of suggestions available is 5, how
many would you like to see?
 2

tandem  WITH A SPACING
   OF 1 m. placed at 10.183657 m. from tractor rear axle.
single and tandem  WITH A SPACING
   OF 3.0 m. placed at 8.704159 m. from tractor rear axle.
would you like to see the remaining suggestions?
 yes ◂                    no
```

```
↑ ↓ ↕    Enter to select    END to complete    /Q to Quit    ? for Unknown
```

```
YOU HAVE TO CHANGE TRAILER AXLE CONFIGURATION.
PLEASE PRESS RETURN TO RESUME WITH CONSULTATION
CURRENTLY LOOKING FOR POSSIBLE SOLUTIONS. PLEASE WAIT.
the total number of suggestions available is 5, how
many would you like to see?
 2

tandem  WITH A SPACING
   OF 1 m. placed at 10.183657 m. from tractor rear axle.
single and tandem  WITH A SPACING
   OF 3.0 m. placed at 8.704159 m. from tractor rear axle.
would you like to see the remaining suggestions?
 yes ◂                    no

tridem or equivalent  WITH A SPACING
   OF 2.4 placed at 10.183657
single and tridem  WITH A SPACING
   OF 5.4 placed at 7.549348
four or more  WITH A SPACING
   OF 3.6 placed at 10.183657
```

```
1Help    2Go     3WhatIf   4Variable 5Rule    6Set     7Edit    8Quit
1Help 2How? 3Why? 4Slow 5Fast 6Quit
```

5.3.3 Validation of results

The results given in the previous section can be validated in many aspects. The first point to check for, is that the expert system does indeed perform the task expected of it. The requirement specifications were defined in Chapter 3. As can be seen from the results provided, the expert system does indeed satisfy these requirements. The second point of importance, is the correctness of the results. This requirement can be checked in two ways. The first way is to check the dimension and load limits displayed by the expert system and checking them against the regulation tables in Appendix A. This is to insure that the limits given by the expert system actually represent those specified by the regulations. The second way to check is to compare the actual loads and dimensions to the limits given. This is to insure that the conclusion made by the expert system concerning the legality of a certain load or dimension is correct. If the expert system provides semitrailer axle group suggestions, the validity of these suggestions can be checked by choosing one and running the expert system to check for the legality of that configuration.

The above methods were used in the validation of this expert system. However, it should be noted that since not every possible combination was tested, the possibility of certain errors that went unnoticed cannot be completely ruled out. As is the case with most expert systems of this nature, more confidence is gained in the system, the more it is used. This is because the more the expert system is used, and the answers validated, the more combinations are actually being tested and the system cleared of more errors.

5.4 Advantages and Limitations of KBS: VELSAS

The advantages of VELSAS can be clearly seen when consulting the system. The problem solved by this KBS is twofold. First it determines the legality of the vehicle in all the required aspects according to the government regulations. Going through this process manually is actually quite cumbersome as there are many points to check for and many methods to follow and exception to take into account. Moreover the person performing this task has to be familiar with the terms used and the regulations applicable. VELSAS, however requires only basic information about the vehicle which is usually available to the person concerned with the vehicle legality. Thus no special knowledge or skill is required by the user.

The more apparent advantage is when the semitrailer axle load or vehicle gross weight is illegal and the user needs to find an alternative configuration. Without consulting the expert system the user would have to go through many steps. First the cause of the problem should be identified. This may be the semitrailer axle group, axle spacing, axle position, tire capacity or any combination of the three. Once the problem(s) is identified, the user has to choose a semitrailer axle group that will solve these problems. The difficulty here is insuring that in satisfying one requirement, another is not being violated. The position of the new axle group is very important in this case. This is because the position influences the actual load on the trailer axle group as well as the tractor axle loads. Thus if, the user chooses the axle group based on the actual axle load, he has to position such that the load on the trailer axle group remains unchanged. If not, then the axle loads have to be calculated once more and the vehicle load legality checked again. Thus choosing a suitable axle configuration can be a lengthy process. However, this process is carried out very quickly by the VELSAS and the user is provided with as many choices as available to choose from.

The most obvious limitation of this KBS is the fact that the solutions provided are limited to changes made on the semitrailer axle group. It is possible to have solutions in which both the tractor and semitrailer axles are modified. However, this requires a different approach in which the semitrailer and tractor axle loads are interrelated.

At present, KBS:VELSAS concludes the consultation process once the sensitivity analysis of the vehicle is done. Following the sensitivity analysis, the user may want to change one or more vehicle parameters. It would be useful if, following these changes, VELSAS, can inform the user how these changes would affect the legality of the vehicle.allowed to change the desired parameters

Another limitation of this expert system is that a change in the regulations, depending on how drastic it is, may leave this expert system with very little use as is. This is because, unlike other fields such as in design or medicine, the knowledge in the expert system is largely dependant on laws and regulation which are more apt to change. Finally, this expert system has to be updated again if it is to be used after December 1994. This is because some of the regulations it represents are not valid after this date.

5.5 Summary

In this chapter, the overall structure of the KBS:VELSAS is presented. The system is evaluated and some test cases presented. The evaluation process includes verification, validation and a presentation of advantages and limitations of the KBS:VELSAS. The verification and validation process consists of requirements definition, verification of the knowledge base, preparation of test cases followed by execution and evaluation of results. Finally, the advantages and limitations of KBS:VELSAS are discussed.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

6.1 Highlights of Thesis

The purpose of this thesis is to develop a Knowledge-Based System: VELSAS that will provide advice as to the legality (weights and dimensions), of tractor-semitrailers operating in Quebec and to evaluate the roll stability and sensitivity of these vehicles. This was achieved by integrating an expert system that specializes in studying the legality of the vehicle with external Fortran programs that evaluate the steady turning roll stability and sensitivity of a given vehicle.

The primary function of KBS: VELSAS is to determine whether a certain vehicle is legal or not. If the vehicle is found to be illegal, VELSAS suggests certain modifications to the vehicle in order to make it legal. The development of VELSAS, required the study of all the relevant laws and regulations defined by the government. This was necessary in order to determine the nature of problem at hand and to define more specific goals of the KBS. Since the choice of the right expert system tool or shell is a key point in building a good KBS, a study of a few commercially available expert system tools and shells was necessary. The study narrowed the choice down to two tools, VP-EXPERT and EXSYS. A prototype of the KBS was built using each of these two tools, and VP-EXPERT was chosen as the development tool. The KBS was then developed following a cycle of prototyping, requirements redefinition, verification and validation. Finally, the finished product was tested and validated and the results of some runs provided.

To study the roll stability of a vehicle for steady turning and to evaluate the sensitivity of a given vehicle to parametric changes, a mathematical model known as the static roll model (SRM) was used. This model determines the rollover threshold for a given vehicle undergoing a steady turning maneuver. A survey of previous sensitivity analysis studies shows that some parameters are more sensitive than others. In all of these studies, repetitive running of SRM was required every time a certain parameter was changed. In this study, a mathematical sensitivity analysis was developed in order to avoid the need for such repetitive running of SRM. For this purpose, the equations for the sensitivity analysis were derived from the static roll model. A mathematical sensitivity analysis was then performed on a vehicle to predict the rollover threshold, rollover angle and the corresponding lateral acceleration. The predicted results were compared to the actual results obtained by running SRM. The results for the more sensitive parameters are provided and the errors involved are discussed.

6.2 Conclusions

- A KBS that acts as an advisor on the legality (weights and dimensions) of tractor-semitrailers in Quebec proved to be both efficient and useful.
- A survey of possible expert system tools and shells resulted in choosing VP-EXPERT as the development tool.
- The integration of the KBS with external FORTRAN programs provides the user with a means of evaluating a given vehicle in three aspects, legality, stability and sensitivity.
- Mathematical sensitivity analysis provides a good estimation of the effect of changing a certain parameter on the rollover threshold while avoiding the need of repetitive running of SRM.
- The error resulting form using mathematical sensitivity analysis increases as the change in the parameter increases.
- The magnitude of error resulting form using mathematical sensitivity analysis depends on the parameter chosen as well as the magnitude and direction of parameter change.
- Mathematical sensitivity analysis cannot be used to predict roll angles larger than the roll angle for the vehicle with baseline parameter set.

6.3 Recommendations for Future Work

The Knowledge-Based System developed, proves the usefulness of such a system for the application at hand. Similarly, the mathematical sensitivity analysis developed provides a good estimate of the effect of changing a certain parameter on vehicle stability. However, a more complete KBS can be obtained by implementing the following suggestions:

- Include the possibility of modifications in axle load and dimensions for the tractor. This can be done by shifting the fifth-wheel position.
- If the vehicle stability is not satisfactory, recommend change in parameters that will ensure stability of the vehicle, then recheck the vehicle legality for the new parameter set.
- Examine the possibility of shifting the payload, as a solution when tractor or semitrailer axle loads are illegal.
- When suggesting shifting the semitrailer axle group as a solution, provide the user with the new axle group position that would not violate the tractor legality.
- Expand the KBS to cover other heavy vehicle types and other provinces.
- Perform mathematical sensitivity analysis on weight variables.
- Examine the possibility of changing more than one parameter at a time and the error involved.

REFERENCES

1. Ervin, R.D. and Guy, Y. "The Influence of weights and Dimensions on the Stability and Control of Heavy Duty Trucks in Canada," Volume 1-Technical Report, UMTRI-86-35/I, University of Michigan Transportation Research Institute.

2. Clarke, R.M., "Truck Safety - an Agenda for the Future," SAE Publication No P-181, 1986, pp. 221-224.

3. Mallikarjunarao, C., "Road Tanker Design: Its Influence in The Risk and Economic Aspects of Transporting Gasoline in Michigan," Ph.D Thesis, University of Michigan, 1982.

4. Wong, J. Y. and El-Gindy, M. "A Comparison of Various Computer Simulation Models for Predicting Lateral Dynamics Behaviour of Articulated Vehicles," RTAC Report, 1986.

5. Bedard, J.T., "Vehicle Rollover Threshold Evaluation: An Assessment of Computer Models , Vehicle Weight and Dimensions Study, Volume 12.

6. El-Gindy, M. and Hosamel-deen, Y. "Sensitivity Parametric Analysis of UMTRI Static Roll Model.", Int. J. of Vehicle Design, 10, 1989, pp. 187-209.

7. Ervin, R. D. "The influence of Size and Weight Variables on the Roll Stability of Heavy Duty Trucks," SAE Paper 831163, 1983.

8. GAZETTE OFFICIELLE DU QUÉBEC, September 25, 1991, vol. 123, No. 39.

9. VEHICLE LOAD AND SIZE LIMITS GUIDE, Gouvernement du Québec, Ministére des Transports, Direction du transport routier des marchandises.

10. Nalecz, A. G. "Application of Sensitivity Analysis and Synthesis of Vehicle Dynamic Systems," Vehicle System Dynamics, 18, 1989, pp. 1-44.

11. Douglas, M. and Emir, M. "System of Personalized Learning Using a Structural Engineering Knowledge Base," Department of Civil Engineering, Concordia University.

12. CRIM annual report 1988-89.

13. Hart, Anna "Knowledge elicitation: issues and methods," Computer Aided Design, 17, 1985, pp. 445-4462.

14. Ebrahimi, Mostafa, "A Structural Approach to Expert System Design," IEEE Western Conference of Expert Systems, 1987, pp.18-24.

15. Allen, R.H., Boarnet, M.G., Culbert C.J. and Savely, R.T. "The Nature and Evaluation of Expert System Tools for Engineering Applications," Computers in Engineering, 1, 1987, pp. 143-154.

16. Martin, James and Oxman, Steven, Building Expert Systems A Tutorial, Prentice Hall, 1988.

17. Jackson, Peter, Introduction To Expert Systems, Addison-Wesley, 1986.

18. Dym, Clive L. and Levitt Raymond E., Knowledge-Based Systems In Engineering, McGraw-Hill, 1991.

19. VP-EXPERT User Manual

20. EXSYS User Manual

21. Sankar, S., Dhir, A. and Shankala, V.S. "Simulation and Field Testing of Tracked Vehicle Suspension Dynamics," Advanced Automotive Technologies-1991, ASME DE-Vol. 40, pp. 423-436, 1991.

22. Ayel, M. and Laurent J.P., Validation, Verification and Test of Knowledge-Based Systems, John Wiley & Sons, 1991.

23. Green, C. and Keyes, M. "Verification and Validation of Expert Systems," IEEE Western Conference On Expert Systems, 1987, pp. 38-43.

24. Boose, J. and Gaines, B. The Foundation of Knowledge Acquisition, ACADEMIC PRESS, 1990.

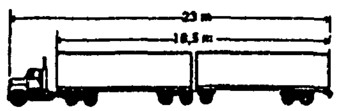
APPENDIX A

EXAMPLES OF QUÉBEC REGULATIONS (Weights and Dimensions)

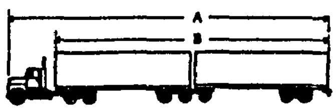
USED IN BUILDING KBS: VELSAS

MAXIMUM DIMENSIONS (continued)

II) Tractor, one semitrailer and one trailer



III) Tractor and 2 semitrailers

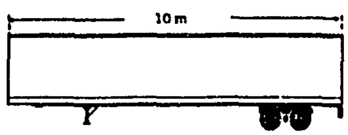


A - 25 m maximum on divided highways;
- 23 m maximum on other roads;

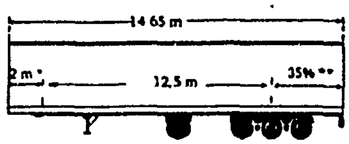
B - 20 m maximum on divided controlled access highways and highway 185;
- 18,5 m maximum on the rest of the network.

E) Semitrailer

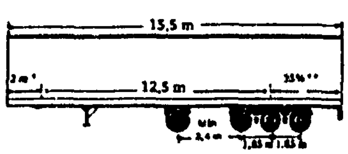
Authorized for all axle classes:



Authorized for all axle classes with the described requirements:



Authorized for single, tandem, or triple axles and for axle classes B.44 and B.45 with the described requirements:



* Setting of the kingpin (radius: 2 m maximum).

** Maximum 35% of the distance between the centre of the single, tandem or triple axle and the centre of the kingpin.

TABLE 1
AXLE LOAD

Class		Normal period (raw forest products)	Normal period (other load)	Thaw period
B.1	Front single axle 	9 000 kg	9 000 kg	9 000 kg
B.2	Front tandem axle 	16 000 kg[1]	16 000 kg[1]	16 000 kg
B.3	Front multiple axle 	15 000 kg[1]	15 000 kg[1]	15 000 kg
B.10	Single axle ●	10 000 kg	10 000 kg	8 000 kg
B.20	Two axles or more ● ○ ● |←d→| d < 1 m	10 000 kg	10 000 kg	8 000 kg
B.21	Tandem axle ● ● |←d→| 1m ≤ d < 1,5 m	17 500 kg[2]	17 500 kg	14 500 kg[4]
B.22	Tandem axle ● ● |←d→| 1,5 m ≤ d < 1,8 m	20 000 kg	18 000 kg[3]	15 000 kg[4]
B.23	Tandem axle ● ● |←d→| 1,8 m ≤ d < 2,4 m	20 000 kg	19 000 kg[3]	15 500 kg

1 Until December 31, 1994, this load limit is increased to 17 500 kg for the axles of a vehicle belonging to a year model prior to 1992

2 Until December 31, 1999, this load limit is increased to 20 000 kg for the axles of a vehicle belonging to a year model prior to 1992

3 This load limit is increased to 20 000 kg for the axles of a single-unit road vehicle used for snow and ice removal on public roads, for the axles of a backloading refuse-compacting trucks et for the axles of a single-unit road vehicle with a non-detachable dumping mechanism carrying sand, earth, gravel, stone sodium chloride, snow, ice or hot mix asphalt

4 This load limit is increased to 15 500 kg on divided highways

TABLE 1 (continued)
AXLE LOAD

Class		Normal period (raw forest products)	Normal period (other load)	Thaw period
B.34	Triple axle or equivalent group of axles ●●● |← d →| 4,2 m ≤ d < 4,8 m	29 000 kg[1]	27 000 kg	23 000 kg
B.35	Triple axle or equivalent group of axles ●●● |← d →| d ≥ 4,8 m	30 000 kg	30 000 kg	24 500 kg
B.36	Single axle in front of a tandem axle ● ●● |← d →| 3 m ≤ d < 3,6 m	22 000 kg[2]	20 000 kg[2]	20 000 kg
B.37	Single axle in front of a tandem axle ● ●● |← d →| 3,6 m ≤ d < 4,2 m	24 000 kg[2 ou 3]	22 000 kg[2 ou 4]	22 000 kg
B.38	Single axle in front of a tandem axle ● ●● |← d →| 4,2 m ≤ d < 4,8 m	26 000 kg[2 ou 3]	24 000 kg[2 ou 4]	22 000 kg
B.39	Single axle in front of a tandem axle ● ●● |← d →| d ≥ 4,8 m	29 000 kg[5]	27 000 kg[2]	22 000 kg

1 Until December 31, 1994, this load limit is increased by 500 kg for the axles of a vehicle belonging to a year model prior to 1992

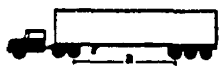
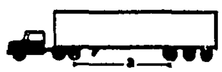
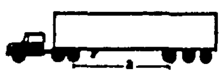
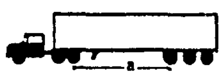
2 Until December 31, 1994, this load limit is increased by 2 000 kg

3 Until December 31, 1994, this load limit is increased by 3 500 kg for the axles of a vehicle belonging to a year model prior to 1992

4 Until December 31, 1994, this load limit is increased by 3 000 kg for the axles of a vehicle belonging to a year model prior to 1992

5 Until December 31, 1994, this load limit is increaded by 1 000 kg

TABLE 2 (continued)
GROSS VEHICLE WEIGHT

Class		Gross weight limit	Designated distance
A.42	 B.32	50 500 kg	a ≥ 5,3 m
A.43	Same vehicle combination as A.42	50 500 kg	a < 5,3 m *
A.44	 B.33	52 500 kg	a ≥ 5,7 m
A.45	Same vehicle combination as A.44	52 500 kg	a < 5,7 m *
A.46	 B.34	54 500 kg	a ≥ 6,2 m
A.47	Same vehicle combination as A.46	54 500 kg	a < 6,2 m *
A.48	 B.35	55 500 kg	a ≥ 6,3 m
A.49	Same vehicle combination as A.48	55 500 kg	a < 6,3 m *
A.50	 B.36	49 500 kg	a ≥ 5,1 m
A.51	Same vehicle combination as A.50	49 500 kg	a < 5,1 m *
A.52	 B.37	51 500 kg	a ≥ 5,4 m
A.53	Same vehicle combination as A.52	51 500 kg	a < 5,4 m *

* The gross weight limit for this class is reduced by 650 kg for each full 300-mm section less than the prescribed distance

APPENDIX B

ELEMENTS OF COEFFICIENT MATRIX [A]

ELEMENTS OF COEFFICIENT MATRIX [A]

The elements of the coefficient matrix [A] used in equation (4.33) are as follows:

$A(1,1) = -(WAXL_1 - W_{U1})ZR_1(1 - \phi_{U1}(\phi_{S1} - \phi_{U1})) + W_{FR}Z_{FR}$

$A(1,2) = -(K_{11} + K_{12})S_1^2 + (F_{11} + F_{12})Z_{R1} - K_{FR} - W_{FR}Z_{FR1}$

$A(1,3) = K_{FR}$

$A(1,4) = (K_{11} + K_{12})S_1{}^2 + (WAXL_1 - WU_1)Z_{R1}(1 + a_y(\phi_{S1} - \phi_{U1}))$
$-(F_{11} + F_{12})Z_{R1}$

$A(1,7) = (K_{11} - K_{12})S_1$

$A(2,1) = -(WAXL_2 - W_{U2})Z_{R2}(1 - \phi_{U2}(\phi_{S2} - \phi_{U2}))$
$-W_{FR}Z_{FR2} \cdot\cdot W_5Z_{52}$

$A(2,2) = K_{FR}$

$A(2,3) = -(K_{21} + K_{22})S_2^2 + (F_{21} + F_{22})Z_{R2} - K_{FR} + W_{FR}Z_{FR2} - K_5$
$+ W_5Z_{52}$

$A(2,5) = (K_{21} + K_{22})S_2^2 + (WAXL_2 - W_{U2})Z_{R2}(1 + a_y(\phi_{S2} - \phi_{U2}))$
$- (F_{21} + F_{22})Z_{R2}$

$A(2,8) = (K_{21} - K_{22})S_2$

$A(3,1) = -(WAXL3 - W_{U3})Z_{R3}(1 - \phi_{U3}(\phi_{S3} - \phi_{U3})) - W_5Z_{53}$

$A(3,3) = K_5$

$$A(3,6) = (K_{31} + K_{32})S_3^2 + (WAXL_3 - W_{U3})Z_{R3}(1 + a_y(\phi_{S3} - \phi_{U3})) - (F_{31} + F_{32})Z_{R3}$$

$$A(3,9) = (K_{31} - K_{32})S_3$$

$$A(3,16) = -(K_{31} + K_{32})S_3^2 + (F_{31} + F_{32})Z_{R3} - K_5 + W_5Z_5$$

$$A(4,1) = -(WAXL_1 - W_{U1})HR_1 - WU_1HU_1$$

$$A(4,2) = (K_{11} + K_{12})S_1^2$$

$$A(4,4) = -(K_{11} + K_{12})S_1^2 + WAXL_1R_1 + (WAXL_1 - W_{U1})ZU1 - KT_{11}(T_1 + A_1)^2 - KT_{12}T_1^2 - KT_{13}(T_1 + Y_1)^2 - KT_{14}(T_1 + A_1 + Y_1)^2 - KOVT_{13} - KOVT_{14}$$

$$A(4,7) = -(K_{11} - K_{12})S_1 + (WAXL_1 - W_{U1})(a_y - \phi_{U1})$$

$$A(4,10) = (KT_{11} - KT_{14})(T_1 + A_1) + (KT_{12} - KT_{13})T_1 - (KT_{13} + KT_{14})Y_1 + WAXL_1a_y$$

$$A(4,13) = -[(F_{Z13} + F_{Z14}) + ((KT_{13} + KT_{14})(T_1 + Y_1) + KT_{14}A_1)\phi_{U1}]$$

$$A(5,1) = -(WAXL_2 - W_{U2})HR_2 - W_{U2}HU_2$$

$$A(5,3) = (K_{21} + K_{22})S_2^2$$

$$A(5,5) = -(K_{21} + K_{22})S_2^2 + WAXL_2R_2 + (WAXL_2 - W_{U2})ZU_2 - KT_{21}(T_2 + A_2)^2 - KT_{22}T_2^2 - KT_{23}(T_2 + Y_2^2) - KT_{24}(T_2 + A_2 + Y_2)^2 - KOVT_{23} - KOVT_{24}$$

$$A(5,8) = -(K_{21} - K_{22})S_2 + (WAXL_2 - W_{U2})(a_y - \phi_{U2})$$

$$A(5,11) = (KT_{21} - KT_{24})(T_2 + A_2) + (KT_{22} - KT_{23})T_2 - (KT_{23} + KT_{24})Y_2 + WAXL_2 a_y$$

$$A(5,14) = -[(F_{Z23} + F_{Z24}) + ((KT_{23} + KT_{24})(T_2 + Y_2) + KT_{24}A_2)\phi_{U2}]$$

$$A(6,1) = -(WAXL_3 - W_{U3})HR_3 - W_{U3}HU_3$$

$$A(6,6) = -(K_{31} + K_{32})S_3^2 + WAXL_3R_3 + (WAXL_3 - W_{U3})ZU_3 - KT_{31}(T_3 + A_3)^2 - KT_{32}T3^2 - KT_{33}(T_3 + Y_3)^2 - KT_{34}(T_3 + A_3 + Y_3)^2 - KOVT_{33} - KOVT_{34}$$

$$A(6,9) = -(K_{31} - K_{32})S_3 + (WAXL_3 - W_{U3})(a_y - \phi_{U3})$$

$$A(6,12) = (KT_{31} - KT_{34})(T_3 + A_3) + (KT_{32} - KT_{33})T_3 - (KT_{33} + KT_{34})Y_3 + WAXL_3 a_y$$

$$A(6,15) = -[(FZ_{33} + FZ_{34}) + ((KT_{33} + KT_{34})(T_3 + Y_3) + KT_{34}A_3)\phi_{U3}]$$

$$A(6,16) = (K_{31} + K_{32})S_3^2$$

$$A(7,1) = -(WAXL_1 - W_{U1})\phi_{U1}$$

$$A(7,2) = -(K_{11} - K_{12})S_1$$

$$A(7,4) = (K_{11} - K_{12})S_1 - (WAXL_1 - W_{U1})a_y$$

$$A(7,7) = K_{11} + K_{12}$$

$$A(8,1) = -(WAXL_2 - W_{U2})\phi_{U2}$$

$$A(8,3) = -(K_{21} - K_{22})S_2$$

$$A(8,5) = (K_{21} - K_{22})S_2 - (WAXL_2 - W_{U2})a_y$$

$$A(8,8) = K_{21} + K_{22}$$

$$A(9,1) = -(WAXL_3 - WU_3)\phi_{U3}$$

$$A(9,6) = (K_{31} - K_{32})S_3 - (WAXL_3 - W_{U3})a_y$$

$$A(9,9) = K_{31} + K_{32}$$

$$A(9,16) = -(K_{31} - K_{32})S_3$$

$$A(10,4) = -(KT_{11} + KT_{12} - KT_{13} - KT_{14})T_1 - (KT_{11} - KT_{14})A_1$$
$$+(KT_{13} + KT_{14})Y_1$$

$$A(10,10) = KT_{11} + KT_{12} + KT_{13} + KT_{14}$$

$$A(10,13) = (KT_{13} + KT_{14})\phi_{U1}$$

$$A(11,5) = -(KT_{21} + KT_{22} - KT_{23} - KT_{24})T_2 - (KT_{21} - KT_{24})A_2$$
$$+(KT_{23} + KT_{24})Y_2$$

$$A(11,11) = KT_{21} + KT_{22} + KT_{23} + KT_{24}$$

$$A(11,14) = (KT_{23} + KT_{24})\phi_{U2}$$

$$A(12,6) = -(KT_{31} + KT_{32} - KT_{33} - KT_{34})T_3 - (KT_{31} - KT_{34})A_3 + (KT_{33} + KT_{34})Y_3$$

$$A(12,12) = KT_{31} + KT_{32} + KT_{33} + KT_{34}$$

$$A(12,15) = (KT_{33} + KT_{34})\phi_{U3}$$

$$A(13,1) = WAXL_1$$

$$A(13,13) = -KYT_1$$

$$A(14,1) = WAXL_2$$

$$A(14,14) = -KYT_2$$

$$A(15,1) = WAXL_3$$

$$A(15,15) = -KYT3$$

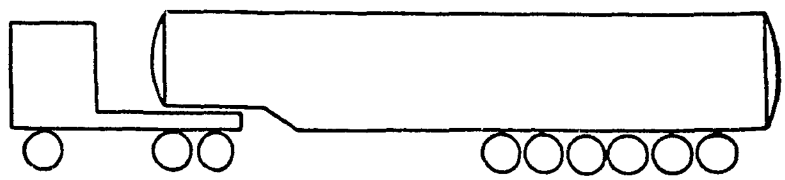
$$A(16,16)=1$$

APPENDIX C

TEST VEHICLE CONFIGURATION AND PARAMETERS

TEST VEHICLE CONFIGURATION AND PARAMETERS

The test vehicle used is a nine-axle tractor semitrailer with the following configuration [6]:



The input data to SRM are:

Total Sprung mass:	(W_s)	112300 [lb]
Weight of the tractor front axle	(W_{U1})	1200 [lb]
Weight of the tractor rear axle	(W_{U2})	4500 [lb]
Weight of the trailer axles	(W_{U3})	6000 [lb]
Load on tractor front axle	($WAXL_1$)	14000 [lb]
Load on tractor rear axle	($WAXL_2$)	32000 [lb]
Load on trailer axles	($WAXL_3$)	78000 [lb]
Half the lateral distance between inner tires on tractor front axle	(T_1)	40.42 [in]
Dual tire spacing on tractor front axle	(A_1)	0.0 [in]
Half the lateral distance between inner tires on tractor rear axle	(T_2)	29.00 [in]
Dual tire spacing on tractor rear axle	(A_2)	13.0 [in]
Half the lateral distance between inner tires on trailer axle	(T_3)	29.00 [in]

Dual tire spacing on trailer axle tires	(A_3)	13.0 [in]
Half the lateral distance between suspension springs on tractor front axle	(S_1)	16.0 [in]
Half the lateral distance between suspension springs on tractor rear axle	(S_2)	19.0 [in]
Half the lateral distance between suspension springs on trailer axles	(S_3)	19.0 [in]
C.G. height of front sprung mass	(ZS_1)	44.0 [in]
C.G. height of rear sprung mass	(ZS_2)	40.0 [in]
C.G. height of trailer sprung mass	(ZS_3)	87.8 [in]
C.G. height of tractor front axle	(ZU_1)	20.0 [in]
C.G. height of tractor rear axle	(ZU_2)	20.0 [in]
C.G. height of trailer axles	(ZS_3)	20.0 [in]
Height of tractor front axle roll center	(HR_1)	22.0 [in]
Height of tractor rear axle roll center	(HR_2)	20.0 [in]
Height of trailer roll center	(HR_3)	28.0 [in]
Height of fifth wheel	(Z_5)	50.0 [in]
Height of tractor frame	(Z_{FR})	34.0 [in]
Vertical Stiffness of one tire on tractor front axle	(KT_1)	5000.0 [lb/in]
Vertical Stiffness of one tire on tractor rear axle	(KT_2)	5000.0 [lb/in]

Vertical Stiffness of one tire on trailer axle	(KT_3)	5000.0 [lb/in]
Auxiliary tractor front roll stiffness	(KRS_1)	0.0 [in.lb/deg]
Auxiliary tractor rear roll stiffness	(KRS_2)	0.0 [in.lb/deg]
Auxiliary trailer roll stiffness	(KRS_3)	0.0 [in.lb/deg]
Tractor frame roll stiffness	(K_{FR})	9000.0 [in.lb/deg]
Tractor frame coulomb friction	(CFR)	11000.0 [in.lb]
Fifth wheel roll stiffness	(M_5)	1000000.0 [in.lb/deg]
Fifth wheel separation moment	(MOM_{SEP})	558000.0 [in.lb]
Lash in fifth plates	($LASH_5$)	2.0 [deg]
Vertical load on fifth wheel	(W_5)	31000.0 [lb]
Tractor rear sprung weight	(W_{S2})	2000.0 [lb]
Lateral stiffness of one tire on tractor front axle	(KYT_1)	3000.0 [lb/in.]
Lateral stiffness of one tire on tractor rear axle multiplied by number of axles	(KYT_2)	6000.0 [lb/in.]
Lateral stiffness of one tire on trailer axle multiplied by number of axles	(KYT_3)	18000.0 [lb/in.]
Overturning stiffness of one tire on tractor front axle	($KOVT_1$)	1000.0 [lb/in.]
Overturning stiffness of one tire on tractor rear axle multiplied by number of axles	($KOVT_2$)	2000.0 [lb/in.]
Overturning stiffness of one tire on trailer axle multiplied by number of axles	($KOVT_3$)	6000.0 [lb/in.]

SPRING TABLES

(a) Tractor Front Suspension

Force (lb)	Deformation
-7500.0	-5.0
7500.0	5.0

(b) Tractor Rear Suspension (grouped)

Force (lb)	Deformation
-24000.0	-4.5
0.0	-1.5
0.0	0.0
36000.0	3.0

(c) Trailer Suspension (grouped)

Force (lb)	Deformation
-75000.0	-4.5
0.0	-1.5
0.0	0.0
144000.0	3.0