FAULT TREE BASED RISK ANALYSIS OF A TRANSMISSION BASED LASER SENSOR FOR INTELLIGENT TRANSPORTATION SYSTEM APPLICATIONS

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ABSTRACT

FAULT TREE BASED RISK ANALYSIS OF A TRANSMISSION BASED LASER SENSOR FOR INTELLIGENT TRANSPORTATION SYSTEM APPLICATIONS

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With the increased difficulty –social, political, and economic – of expanding transportation capacity through conventional infrastructure- building and with the increase of transportation demand and congestion, Intelligent Transportation Systems (ITS) is increasingly considered as a better solution to these problems. Successful operation of ITS application often depends upon the deployment of traffic sensors at various strategic locations on transportation facilities.

The objectives of this research were to develop a laboratory prototype of a reliable transmission-based laser sensor system that would measure the traffic flow parameters and to estimate the sensor system's probability of failure, using fault tree analysis, under various adverse weather conditions, such as fog, smoke and rain.

Though an attempt had been made to assess the probability of failure under adverse weather conditions, it was very difficult to create a laboratory condition that would give the failure probability exclusively for each event. Recent studies related to the various weather conditions had been consulted for the estimation of the system's failure.

The estimated failure probability of the system was 1.966 % giving the system's reliability as 98.034 %. Inclusion of redundancy and more powerful laser diode and photo detector pairs would increase the system's reliabili

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CHAPTER I

INTRODUCTION

Every year billions of dollars are invested in the US for the construction of new, or expansion of existing, transportation facilities to accommodate more automobiles and trucks to ensure fast and safe movement of people and goods. However, the congestion level and travel delay is also increasing every year. Construction can not keep pace with the transportation needs. Motorists drive approximately 2.6 trillion miles each year, which is 80 percent more than they did 20 years ago according to Federal Highway Administration (FHWA) estimation (Sundeen 2002). Another estimation of FHWA states that the total number of drivers has increased by 30 percent since 1980 and it will continue at a rate faster than the overall population growth (Sundeen 2002).

The 225 percent increase of truck travel during the last 30 years has added more traffic on road networks and official prediction is that the rate of truck travel will grow 3 percent annually in the next 20 years, nearly doubling the number of trucks on the road.

Increased traffic congestion as more cars and trucks come on to the existing roads results in a huge traffic delay nationally, which is roughly 4.4 billion hours according to the Texas Transportation Institute (TTI) estimation (http://mobility.tamu.edu.ums).

The costs due to travel delay rose to $78 billion in 1999 in many urban areas, which was far bigger than the $21 billion in 1982 according to TTI. Also, the huge amount of traffic on roads is one of the many reasons for the increase of highway deaths, which was 43,000 in 2003(ITE journal, July 2004).

The traditional approach of building new transportation facilities or adding to the existing ones to mitigate the congestion problem and to accommodate the increased traffic is a less appealing solution to transportation planners due to budget, expense, time and environmental challenges. Intelligent Transportation Systems (ITS) refers to the integrated application of traffic engineering concepts, software, hardware, and communications technologies to the surface transportation system to improve its efficiency and safety (Chowdhury 2003).

Problem Statement

Keeping the traffic flowing does not guarantee future mobility and meeting future traffic demand. Mobility and demand satisfaction should include the impacts of congestion and travel time on the economy, air pollution, noise emission and many other areas. ITS is expected to be a solution to help alleviate these problems. To solve the congestion problem, transportation professionals need a clear picture of the traffic flow which depends largely on the availability of real time traffic data not only at the strategic locations but on the network as a whole. The most important parameters are vehicle count, average speed within a time interval, and the classification of vehicles. Traffic detectors measure all of these necessary parameters to support several ITS functions such as traffic signal control, ramp metering, traveler information development, and freeway management and incident detection.

Though the emergence of numerous technologies in the development of different kinds of traffic detectors over the years, it is clear that traffic detection systems are comprised of four components, namely detection methods, hardware, software and communications. Based on the technology used, the detection method can be either intrusive to the roadway such as inductive loops or non-intrusive such as laser-based systems, closed-circuit cameras, probe vehicles, media, and police and citizen reports. Detection methods also sometimes use environmental sensors to get information about the weather in some particular time period. Conversion of collected raw data into meaningful traffic parameters by using algorithms and communication with field devices through graphical user interface is done by computer software. Finally, the communication system integrates the different components of the control center and provides the links between the control center and the field devices. Current detector technologies can be classified as either intrusive to the roadway or non-intrusive. The examples of intrusive detectors are inductive loop, magnetometer and magnetic detectors, whereas non-intrusive detectors are microwave radar, laser sensors, ultrasonics, acoustics and video image processing.

The inductive loop detectors (ILDs) are the most primitive and the most often used traffic sensors in transportation system management since 1960. ILDs working principle is based on the decrease in loop inductance due to the two opposing magnetic fields. One of them is the loop's magnetic field caused by the loop's current and the other one is the eddy current's magnetic field which opposes the loop's magnetic field. The eddy current is induced from the vehicle residing on the loop. The quality of the basic traffic parameters such as volume, presence, occupancy, speed and gap obtained from loop detectors under favorable weather conditions is good enough but at high expense of installation, maintenance and electronic processing. Moreover, the requirement of closing lanes and re-routing traffic during its installation causes disturbance especially in highly dense traffic areas. In addition to the above disadvantages, ILDs intrusiveness makes it unsuitable for some locations such as bridges. ILDs are sensitive to stress and temperature. Besides these issues, the foremost problem with ILDs is their reliability. Because of their susceptibility to stress, the ILD failure rate is quite high which is in the range of 0.13 to 0.29 per detector per year (Lawrence A. Klein, Sensor Technologies and Data Requirements for ITS, pp-287). The estimate of failure rate includes both the structural and detection failure. Pavement cracks and separation from bottom up or routine maintenance involving removal of few inches of asphalt from where the loop is installed mainly cause the structural failure of ILDs. Due to these reasons, transportation agencies have searched for an effective and inexpensive detection system that can be installed and maintained with minimal disruption of traffic while not sacrificing the reliability and accuracy of the data they depend upon. As a result of their search, non-intrusive detection systems were developed.

To quantify the level of uncertainties with loop detector observations a fuzzy-clustering approach has been developed recently (Ishak 2003) which can help data screening, detector maintenance and re-calibration processes. Although the uncertainty measurement could help identify the operational status and calibration problems and improve the accuracy of the sensor data, their intrusiveness may exclude the possibility of their selection in future transportation systems.

Two-axis fluxgate magnetometer and magnetic detectors (ITE 1990) are two other types of intrusive detectors. The essential part of the magnetometer is the probe embedded in the pavement connected by wire to the pullbox and controller. A quarter of an inch wide and one-inch deep single sawcut that runs across the entire width of the road contains the wire. The probes are placed in one-inch diameter cores in the middle of each directional lane. Detectable voltage change caused by a vehicle passing over the probe sends a signal to the controller. The installation requires pavement cut as does the ILDs. This type of detector cannot perform vehicle classification tasks (Klein 2001).

Magnetic detectors detect the vehicle signature by measuring the distortion in the magnetic flux lines induced by the perturbations in the quiescent earth's magnetic field due to the movement of the metal vehicle. Similar to the loop detectors, the installation requires pavement cut or tunneling under the roadway. Without special layout and signal processing software, this type of detector is not able to detect stopped vehicles (ITE 2000). Magnetic detectors also cannot classify vehicles (Klein 2001).

Pressure pad detection is activated by the weight of a vehicle closing the connection between a contact plate and the connecting cable to the controller. The closed circuit then sends a signal to the controller. The pressure detector is limited in application due to its high expense and its inability to collect all necessary traffic data except traffic count. This is also an intrusive detector.

An intrusive detector's susceptibility to structural failure, including pavement cracks, and during routine maintenance involving the removal of the top few inches of asphalt from the place where loop is installed and the lane closure requirement during installation make transportation system management agencies seer for an effective and inexpensive detection system that can be installed and maintained with minimal disruption of traffic. From the outcome of the search for an alternative detection system emerges the non-intrusive detection device. Non-intrusive detection devices are not embedded in pavement; instead, they are mounted on a structure over or to the side of the road.

Microwave radar detectors are non-intrusive detectors and their installation does not require pavement cut. Microwave detectors perform well in all weather conditions as they are not sensitive to weather conditions but their main disadvantage is that they can't detect stopped vehicles. There are two types of microwave radar detectors based on their transmitted electromagnetic wave. As these types of detectors are installed above ground surface they are not subject to the effects of ice and plowing activities. Microwave radars have shown acceptable performance in inclement weather conditions such as rain, snow, fog and wind (klein 2001).

Another non-intrusive detector device is the infrared sensor, which usually employs laser diodes and in certain cases (active type) light emitting diodes (LEDs). Both the laser diodes and LEDs operate in the near infrared spectrum. Infrared sensors are of two kinds: active detectors and passive detectors (FHWA 2000). Active infrared sensors have similarity to microwave radar detectors as both of them transmit a narrow beam of energy towards a roadway surface. The detection technique is based on the reflected beam from the vehicle presence in the detection zone. Though there is no commercial model of active infrared sensor in the US market, which employs LED as the energy source, there exists one prototype sensor system based on two transmitter receiver systems and modulated LEDs to measure speed and height of trucks. Modulated signal prevents interference from other sources transmitting infrared energy. Active infrared sensors transmit multiple beams within a detection zone to measure traffic parameters like volume, lane occupancy, speed, length assessment, queue measurement and classification. The main disadvantage is degradation of performance in certain weather condition such as fog or snow (Klein 2001).

Passive infrared sensors do not emit energy; rather, they detect energy, which is emitted or reflected from vehicles, road surfaces, and other objects. Energy sensitive detection elements on the focal plane of non-imaging infrared passive sensors gather energy from the entire scene. Passive infrared sensors with a single detection zone can measure volume and lane occupancy whereas those with multiple detection zones can measure speed and length. Degradation of performance in adverse weather condition such as sunlight, fog, haze, snow, smoke and dust is one of several disadvantages of these types of sensors.

Pressure waves of sound energy above human audible range are transmitted and the reflected energy towards the sensor is detected in Ultrasonic non-intrusive sensors. Pulse waveform is generally used in most of the models. They are capable of providing vehicle count, presence and lane occupancy. Moreover these types of detectors are able to serve multiple lanes and can detect over-height vehicles. Environmental conditions like temperature and air turbulence affect their performance.

The interaction of a vehicle's tires with the road surface and the variety of sounds from a vehicle in traffic generate acoustic energy or audible sound, detection of which by an acoustic detector gives the detector's capability of measuring speed, volume, occupancy and presence. Acoustic detectors use a system of microphones to pick up the generated sounds from a focused area near a lane or a roadway. A signal-processing algorithm can detect the increase in sound energy due to the passage of a vehicle through the detection zone and a vehicle presence signal is initiated. The vehicle presence signal is terminated when the sound energy in the detection zone drops below the detection threshold as the vehicle leaves the detection zone. The acoustic sensor's ability to work in all light conditions and during adverse weather gives an advantage position compared to other detector technologies.

The transportation community had considered video detectors as their choice of detection devices due to their capabilities of monitoring multiple lanes and providing wide area detection. However their performance was degraded in inclement weather conditions such as fog, snow, rain, day-to-night transition, and glare at dawn and dusk. The traffic count by this type of detector missed tailgaters according to a study (Habina 2002). Another study found that parallax error, a distance- related measurement error, occurred in the video detector as it had to rely on field of view for its measurement reading and could cause 10 to 50 percent erroneous data on a normal camera setup (Tian and et.al 2002).

The U.S. transportation community has not accepted any particular detector, as its most preferred one because of the disadvantages associated with available systems. An infrared sensor could be a simple and cost-effective tool to assess traffic flow parameters. The proposals of other researchers involving infrared detectors were based on the reflection of the signals, which required a long distance of propagation and might cause excessive attenuation, diffraction, and scattering of the signal. The developed infrared sensor was transmission based rather than reflection based and provided reliable estimates of vehicle position, speed and classification, and it did not need to rely on proper aiming of a laser beam to get good reflection. The laboratory prototype of the new sensor was modeled by fault tree analysis to check the detector's robustness under various unfavorable conditions, which might cause failure of the detector in field. As a result, the developed system was able to alleviate the problems associated with infrared sensor deployments and was a simple and convenient tool to support managing freeway operations, traffic signal operation, ramp metering, work zone traffic monitoring and traveler information system development.

Objectives

The general objective of this research was to develop and evaluate a reliable transmission-based laser sensor using fault-tree analysis, and to refine the system design.

Literature Review

Previous research on the transmission-based laser sensor system and performances in various inclement weather conditions are discussed in this section. A field prototype based on laser-based non-intrusive detection method was tested at the University of California, Davis (Cheng, et al, 2001). This prototype was capable of measuring the delineations of moving vehicles. Vehicle speed was measured with the help of two laser transmitter/detector pairs installed at a known distance apart. The test results validated the detection method and the algorithm used in the prototype. The sensor system was able to measure velocity, acceleration and vehicle length traffic parameters.

Evaluation of the operation of overhead infrared laser sensors under heavy traffic and adverse weather condition was done at New York toll booths (Tropartz, et al, 1999). About 2.3 million vehicle classifications were made with an accuracy of 98.5%. This sensor system was developed using passive technology which collects reflected light from the pavement into a photodiode and the absence of the reflected light meant vehicle presence.

Research by Harlow et al (1997) used a laser sensor system that returned range and intensity image information. This information was used to classify vehicle parameters such as vehicle's length, width, height and speed. In this study a series of known vector lengths and projecting lasers at various pre-determined angles were used to classify vehicles such as automobile, van, pickup-truck or sports utility vehicle by differences in their heights above the roadway in relationship to their measured length. The algorithm used in this study considered additional features on the back of the vehicle on the assumption that the rear area of a vehicle varies considerably by vehicle type. Harlow used range imagery laser sensors and had a classification accuracy of over 92%.

Attenuation of optical lasers in the visible and IR region due to fog was studied by Maher, et al (2004). This study focused on the disturbing role of atmosphere on light propagation and thus on the channel capacity, availability and link reliability. Light propagation through the atmosphere is affected at the same time by absorption and scattering caused by atmospheric constituents (molecules and aerosols).These scattering and absorption cause the loss of a part of the transmitted power of light, called attenuation. The power loss of light is exponential in nature with the distance from the source of light in such a manner that can be described as the ratio of received power at a distance L to the emitted power called total transmittance of the atmosphere and it is wavelength dependent. Total transmittance is a function of distance from light source L and a coefficient called attenuation or total extinction. Total transmittance is a number that can be calculated as the transcendental number; e raised to a power equal the negative of multiplication result of extinction coefficient and the distance from the light source. To know the received power at a distance L from the source, extinction coefficient needs to be determined. In this study it is the extinction coefficient (due to fog) that was determined from both an empirical and theoretical point of view in the visible and IR regions. The authors classified fog based on their visibilities and found that for dense fog (visibility < 500 m) the wavelength of the light in IR and visible region and the particle size of fog was of same order causing Mie scattering. Finally the authors modeled fog of different visibilities with a computer program (FASCOD) and developed graphs of extinction coefficients vs. wavelength of light for each fog of a certain visibility. In this study both advection and radiation fog were considered. From these graphs for a light of known wavelength, a visibility extinction coefficient can be determined which helps calculating the light attenuation at a known distance L.

Attenuation of IR light waves caused by rainfall while it propagates through the atmosphere was studied by Maha (2004). Due to the larger drop size of rain than the wavelength of IR light, rainfall causes non-selective scattering which is wavelength independent. Like fog attenuation, rainfall attenuation is also composed of absorption and scattering components of which absorption is negligible as the most abundant gases (nitrogen and oxygen) do not have any absorption bands in this wavelength. Rainfall attenuation is mainly caused by scattering of light by rain droplets. Unlike attenuation due to fog where limited visibility is the main reason of attenuation, attenuation due to rain is based upon rainfall rate, relative humidity and temperature. In estimating the scattering coefficient a simulation had been done using Simulight software. Rainfall drop size distribution was approximated by Weibull distribution and a plot of rainfall attenuation coefficient vs. rainfall rate had been drawn to calculate the attenuation for any rainfall rate.

Scope

This research focused on the development of a reliable transmission-based laser sensor for Intelligent Transportation Systems (ITS) application. As light propagation through atmosphere could attenuate in adverse weather such as fog or rain, the performance of a laser sensor could also be deteriorated significantly. To develop a reliable sensor, a prototype of the sensor was modeled in the laboratory and its failure probability has been estimated under adverse weather conditions.

CHAPTER II

THEORETICAL CONCEPT

Traffic flow consists of interacting individual drivers and vehicles and other geographical and physical elements of the roadway. As all of these can vary widely, dealing with traffic streams involves an element of variability. Description of traffic stream quantitatively requires understanding of this inherent variability and also knowledge of normal ranges of these parameters. The subsection "Measurement of Traffic Flow Parameters" describes the parameters most often used for this purpose that constitute a language with which traffic streams are described and understood. The theory of fault-tree analysis is explained in the subsection "Overview of Fault-Tree Analysis" while the subsection "Prototype Development" details the methodology used in the prototype development and this subsection also explains hardware and software of the prototype

Measurement of Traffic Flow Parameters

A traffic stream is described quantitatively with the three basic elements –flow, speed and density. Density is also related to the gap or headway between two vehicles in the traffic stream. A brief definition of these terms is given below:

Flow (q). Flow can be defined as the number of vehicles passing a given point on a highway during a given period of time, typically 1 hour (vehicles per hour).

Speed (u).Speed is the distance traveled by a vehicle during a unit of time. Speed is usually expressed in miles per hour, kilometers per hour or feet per second.

Density (k). Traffic density can be defined as the number of vehicles present over a unit length of a highway at a given instant in time. Density can be measured indirectly by dividing measured traffic flow (vehicles per hour per lane) by speed (miles per hour).

In this research flow, speed and also the size of the passing vehicle were measured with the developed prototype.

Overview of Fault -Tree Analysis

This section describes the basic concepts, construction procedure and evaluation techniques of fault tree analysis necessary to analyze a system's risk. Before going in to the detail of fault tree related issues it is important to argue the justification of analyzing a system from a pessimistic view i.e. "failure" rather than from optimistic view of "success". The operation of a system can be perceived from two different standpoints: the ways it can succeed or the ways it can fail. Failure/success space is depicted in Figure 1 below.

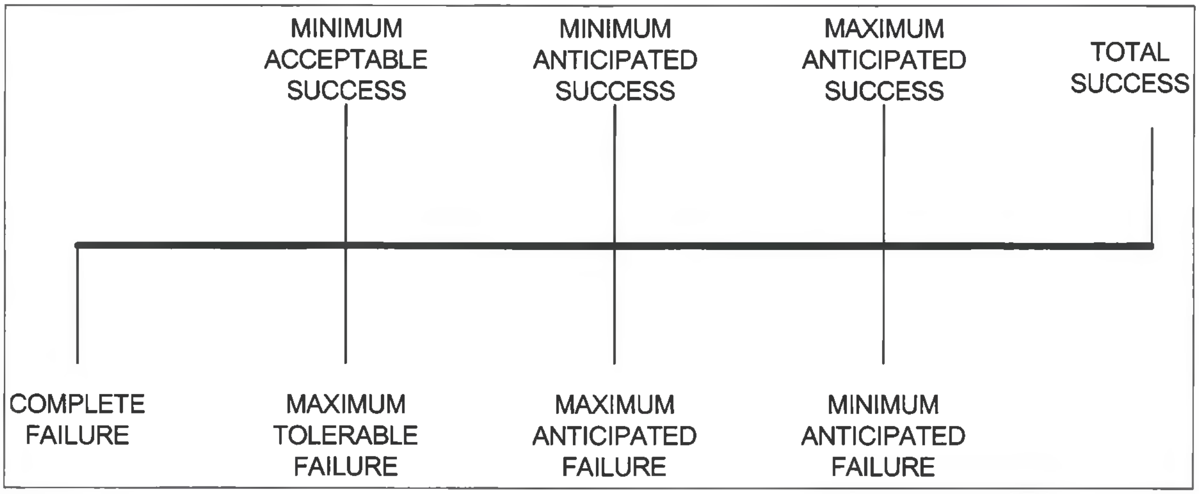


Figure 1: The Failure Space-Success Space Concept. (Fault Tree Hand Book 1981)

A plane that has the capability of flying high for a long distance without refueling with a high speed is desirable and would be an ideal one. But the final design of the plane will definitely fall short of some of its ideal characteristics due to trade-offs, which is always the case in real world. The "success" of the plane can have different meaning to different people but if it crashes, everybody will say the system failed.

The "success" parameters of a system such as output, efficiency, production and marketing features are not easy to model by simple discrete events, such as "valve does not open" which characterizes failure space. This event "failure", particularly “complete failure” is easy to define, whereas the “success” event is not as easy to define and that is why analysis is done in failure space.

Another argument in favor of failure analysis is that although both the number of ways a system can fail or succeed is not finite, the number of ways for the success space is more than that of in the failure space. Consideration of failure space helps analysts to complete their task which otherwise would not be completed. The tree diagram for a large, complex system is very large and if the failure space were considered, only two or three trees would be enough to cover all the possible failures of the system whereas consideration of the success space would require several hundreds of trees. As an example, analysis of the Minuteman Missile system can be mentioned in which three fault trees were done. Careful analysis of these three trees covered the whole complex system.

The selection of an undesired event is the most important factor as it determines the success or failure of a fault tree analysis. The undesired event will be the top event in a fault tree diagram constructed for the system. Generally, it consists of complete, catastrophic failure. The undesired event should be carefully chosen, as if it is too general then the tree will be unmanageably large. On the other hand, a too-specific undesired event cannot give a broad view of the system. To get a clear idea about the selection of a top event, consider the different possible events that Mr.”X” can encounter on his driving to his office from home, which is depicted in the Figure 2.

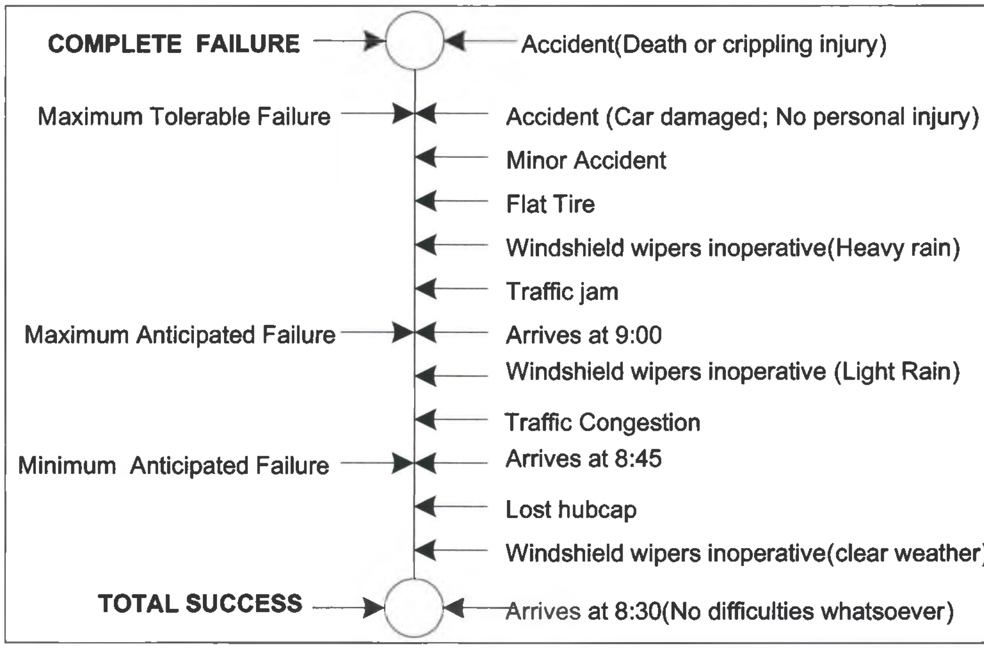


Figure 2: Use of Failure Space in Transport Example (Fault Tree Hand Book 1981)

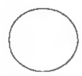
Figure 2 presents "accident that causes death or serious injury" as complete failure, which will be the top event of a fault tree if constructed for his driving mission.

Basic Elements of a Fault Tree

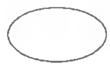
A fault tree is a graphical representation of the faults. It shows the various parallel and sequential combinations of those faults, which result in the predefined undesired event. The faults can be the events that are associated with component hardware failures, human errors, or any other events which can lead to the considered event.

A fault tree is not a model of all possible system failures or all possible causes of system failure. It consists of a top event, which is a particular system failure mode and all possible faults that cause the top event. A fault tree is a qualitative and quantitative model and composed of entities known as “gates”. Gates give permission or inhibit the passage of a fault to go up the tree. It gives the relationship of the events needed to occur for the” higher” event. The higher event is the “output” of the gate; and lower ones are the “input”. A typical fault tree is composed of several symbols that are summarized below in the table 1.

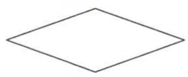
PRIMARY EVENT SYMBOLS



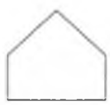
BASIC EVENT – A basic initiating fault requiring no further development.



CONDITIONING EVENT – Specific conditions or restrictions



UNDEVELOPED EVENT – An event which is not further developed either because it is of insufficient consequences or information unavailable.

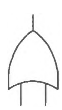


EXTERNAL EVENT – An event which is not further developed either because it is of insufficient consequences or information unavailable.

INTERMEDIATE EVENT SYMBOLS

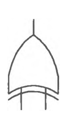
INTERMEDIATE EVENT – A fault event that occurs because of one or more antecedent causes acting through logic gates.

GATE SYMBOLS

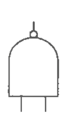


OR– Ouptut fault occurs if at least one of the inputs faults occurs.

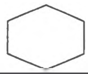
AND – Output fault occurs if all the input fault occurs.



EXCLUSIVE OR- Output fault occurs if exactly one of the input faults occurs.



PRIORITY AND –Output faults occurs if all of the input faults occur in a specific sequence (the sequence is represented by a CONDITIONING EVENT drawn to the right of the gate.



INHIBIT– Output fault occurs if the (single) input fault occurs in the presence of an enabling condition.

Table1: Symbols used in Fault Tree (Fault Tree hand book 1981)

Principle of Fault-Tree Construction

After introducing the symbols used to build a fault tree, the concepts needed to select and define fault tree events will be discussed. Concepts such as fault vs. failure, passive vs. active components, different component failures and relationship among their effects, failure modes, failure mechanisms and failure effect necessary in determining interrelationship among events, and also the immediate cause of a higher event to go a level deeper in the fault tree building process will be discussed in this section.

Faults vs. Failures. "Failure" is a specific word whereas "fault" is a more general word. Using an example will help better understand the distinction between them. Consider the working principle of a clothes dryer machine which is supposed to shut down after the cycle completes and the user opens the door to take out the dry clothes. But if the user opens the door before the cycle completes, then the machine will shut down and the clothes will not dry. The event is not a failure as it is supposed to shut down on door opening which it exactly does. In this system the user is a part of the system and it is his/her untimely action that causes the "fault" event. Both time "when" the undesirable state of the component happens and "what" is the undesirable state are need to be specified in the description of a fault event in the fault tree.

Passive vs. Active Components. Components of a system can be classified as "active" and "passive" based on the way they change the functionality of the system. Passive components provide functionality to a system in a static way while active components are more dynamic. As an example, consider a computer network which consists of hosts such as source and destination; and a transmission medium such as wire or radio. In this system, source host transmits data (signal) to the destination host through transmission media. The main function of the transmission media is to carry the data from the source to destination, but it cannot originate any data and thus it is a passive component of the system; whereas, source and destination hosts are active components, as they can originate data. The failure of a passive component causes non-transmission (static) of the signal whereas failure of active component produces no data at all or incorrect data (dynamic behavior).

Component Fault Categories: Primary, Secondary, and Command. If a fault of a component occurs in an environment for which it was designed then it is called a primary fault. For example a bridge girder designed to withstand a load P fails at a load which is smaller than P.

A secondary fault is any fault of a component that occurs in an environment for which it was not designed. If in the previous example the girder fails at a load greater than P then a secondary fault has occurred.

As primary and secondary faults are normally component failures, they are usually called primary and secondary failures. On the other hand command fault occurs at the proper operation of a component but at the wrong time as in the dryer example given in the "Faults vs. Failure" section.

Failure Mechanism, Failure Mode and Failure Effect. Determination of the proper interrelationships among the events of a fault tree requires the basic concepts of failure effects, failure modes and failure mechanisms. Failure effects explain the importance of a particular failure and its effects on the system. Failure modes show what aspects of component failures are of concern. How a particular failure mode can occur and also, perhaps, what is the corresponding probability of it happening, are described by failure mechanisms. Thus, failure mechanisms produce failure modes which, in turn, have certain effects on system operation. These failure modes constitute the various types of system failures and in the fault tree terminology these are the "top events" that the system analyst can consider. The number of fault trees that a system can have depends on the number of failure modes a system analyst considers and for each of the chosen failure modes in the fault tree.

In analyzing the system failure a system analyst will take one of these top events and define immediate reasons for its occurrence. These immediate reasons are the failure mechanisms for the top event and constitute the second level of the fault tree rooted at the top event. This second level (failure mechanisms just identified) actually constitutes the failure modes of the subsystems and will be the failures of the certain subsystem in the same way as the root was for the whole system. Immediate causes of these failures will constitute the third level of the tree and analysis will proceed in this way until the component failures are reached. These component failures are the basic causes and are defined by the resolution of the tree. All the subsystem and system failures above the component level are failure effects from the point of view of an analyst at component level – that is, they represent the results of particular component failures.

The "Immediate Cause" Concept. The "immediate cause" concept helps in analyzing a system thoroughly and completely so that no event can be dropped from consideration. In the fault tree analysis of a system, a system analyst will define his system boundary first and then select a particular system failure mode for analysis. This system failure mode will be the top event of the fault tree. The immediate, necessary and sufficient causes for the occurrence of this top event will constitute the second level of the tree. These immediate causes should be determined by analyzing the system methodically one-step-at-a-time so that no event can be missed from consideration of the immediate causes of the top event. Due to this methodical incremental analysis, the "immediate cause" concept is sometimes called the "Think Small" Rule.

The immediate, necessary and sufficient causes of the top event are now viewed as sub-top events which will be the top events of the subsystems and their immediate, necessary and sufficient causes will be determined in the same way as before. In doing this system analyst will view the part of the system which are subsystems of the whole system and for which the failure modes (immediate causes) are the failure mechanisms of the whole system.

Proceeding in this way down the tree by continuously changing point of view from mechanism to mode, a system analyst approaches finer resolution in mechanisms and modes until the preset limit of resolution of the tree is reached. The limit is set at component failures and as the inclusion of every possible event is guaranteed by following the immediate cause concept in every step of the analysis, the constructed tree will include all events and failures, and by analysis of this tree will give a good estimate of the probability of occurrence of the top event, i.e. system failure.

Basic Rules for Fault Tree Construction. Though fault tree construction was initially considered as an art, now it is well accepted that a successful tree can be drawn with a set of basic rules described below.

Ground Rule I: "Write the statements that are entered in the event boxes as faults; state precisely what the fault is and when it occurs."

Ground Rule II: "If the answer to the question" Can this fault consist of a component failure?" is "Yes," classify the event as a "state-of-component fault." If the answer is "No", classify the event as a "state-of-system fault."

For the "state-of-component fault" an OR-gate below the event is added and primary, secondary and command modes are sought where as for the "state-of-system fault" any of AND-gate, OR-gate, INHIBIT-gate or no gate is necessary.

Minimum necessary and sufficient immediate cause or causes are looked for in the "state-of-system" fault.

There are three other procedural rules in addition to the above ground rules. The first of these is the NO Miracles Rule:" If the normal functioning of a component propagates a fault sequence, then it is assumed that the component functions normally." The remaining two procedural rules deal with the dangers of not being methodical in the development of fault tree. The first one is Complete – the –Gate Rule:" All inputs to a particular gate should be completely defined before further analysis of any one of them is undertaken." The second one is the No Gate-to-Gate Rule:"Gate inputs should be properly defined fault events, and gates should not be directly connected to other gates."

Fault-tree Evaluation

Once a fault-tree is considered, it is evaluated to get the qualitative and/or quantitative results from it. Evaluation can be done either by manually (small tree) or by computer codes (large tree). In this study only quantitative results were investigated, by which the absolute value of the failure probability of the top event was calculated manually. Calculation of the probability of the failure of the top event was a two-step procedure; the first was to express the top event in terms of the minimal cut sets, and the second was to calculate the probability of failures of the components that were in the minimal cut set expression of the top event. For the first step, the fault tree was represented in terms of Boolean equations. These equations were then used to determine the fault tree's "minimal cut sets". Minimal cut sets defined the" failure modes" of the top event and helped quantify the fault tree. In this section the method of representing the top event of a fault tree in terms of a minimal cut set is explained generally and the application of this method to the fault tree of the sensor system is explained in the section "Evaluate the fault-tree of the sensor to assess risk of failure".

Minimal Cut Sets. A minimal cut set is defined as a smallest combination of component failures which, if all occur, will cause the top event to occur". A minimal cut set is a "smallest" combination of primary events sufficient for the top event to occur and if one of the failures in the cut set does not occur, then top event will not occur. The minimal cut set expression for the top event can be written in the general form, $T = M_1 + M_2 + \ldots\ldots\ldots + M_K$ where T is the top event and M_i are the minimal cut sets.

For determining the minimal cut sets of a fault tree, the tree is first represented in equivalent Boolean expression and then either a "top-down" or a "bottom-up" substitution method is used. In the section "Evaluate the fault-tree of the sensor to assess risk of failure" a "top-down" approach is used to solve the tree.

After getting the minimal cut set expression for the top event, the absolute probabilities of failures of the components are estimated from recent studies and substituted in the expression to get the probability of failure of the top event, i.e the probability of failure of the sensor system.

Prototype Development

Like any system development process, a laboratory prototype of the sensor system was also developed. In this section, the basic theoretical concepts of measuring parameters such as speed, size and count, hardware and software used in this prototype are explained.

Methodology

Knowing the time taken to travel a known distance can give the velocity of any object, which is also true for velocity measurement of a vehicle. To measure the time of travel for the known distance, which is the distance between the lasers placed along one side of roadway, the detectors were placed on opposite sides of the same roadway and by measuring the time taken by a car to travel the distance between the successive lasers the velocity of a car was measured.

Whenever a car came in the path of the laser then the detector could detect the car, as the light beam could not reach the detector. With this technique the time between the blocking of light emanating from each laser was also measured. Also, the measurement of time of residence of a vehicle in the path of a beam could help measure the size of the vehicle if the speed of the vehicle was known. In this method speed monitoring was different from that used in conventional laser guns, where the light is reflected off the license plate or any other reflecting surface of the moving vehicle and the velocity is measured by Doppler shift, as in laser Doppler velocimetry. In the initial proposed framework, shown schematically in Figure 3, two lasers L1 and L2 were placed next to each other with a distance of L apart. The two detectors placed on the opposite side of the road were D1 and D2.These detectors detected the corresponding beam coming to them from the respective lasers, but whenever a vehicle got in the path of the line of sight of the beam it was blocked and the detector detected the presence of the vehicle. The time, τ, between the blocking of light emanating from each laser was measured. Velocity, v was measured by dividing the distance 'L' between the lasers by τ which can be represented in equation form as $v = L/\tau$.

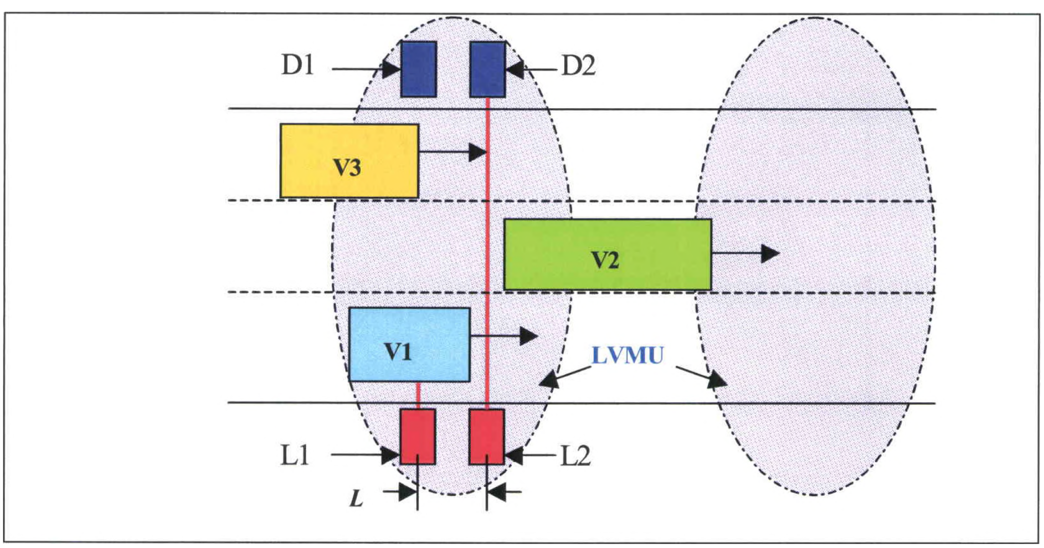


Figure 3: Multi-lane highway with moving vehicles V1, V2 and V3. The laser velocity measurement unit is comprised of two lasers L1, L2 and two detectors D1, D2

The system that consists of the lasers L1 and L2 and the detectors D1 and D2 which shown encircled by the dotted curve in Figure 3 was called Laser Velocity Measurement Unit (LVMU). Flexibility of adjusting the height of the laser source and the detector above the ground surface gave the LVMU a wide range of capabilities in measuring various traffic flow parameters. As an example, if both the laser source and the detectors were set above a few inches off the ground then it could monitor and verify the correctness of the speed measurements.

For multiple lanes, the placement of multiple LVMU was necessary at specific places and the optimum number of LVMU's was determined from the prior knowledge of the number of lanes. In the case of multiple lanes one LVMU might miss adjacent vehicles in different lanes as both of them might block the two beams at nearly the same time, but multiple LVMUs would not miss the adjacent vehicles as another LVMU placed in the downrange would be able to distinguish the two vehicles. Figure 4 shows the extension of LVMU for a single lane(Figure 3) in a case of multiple lanes. In general, it was predicted that the number of detectors needed to positively identify vehicles in a multi-lane highway was at least one grater than the number of lanes. Velocity resolution of the monitoring system was the distance between the detectors.

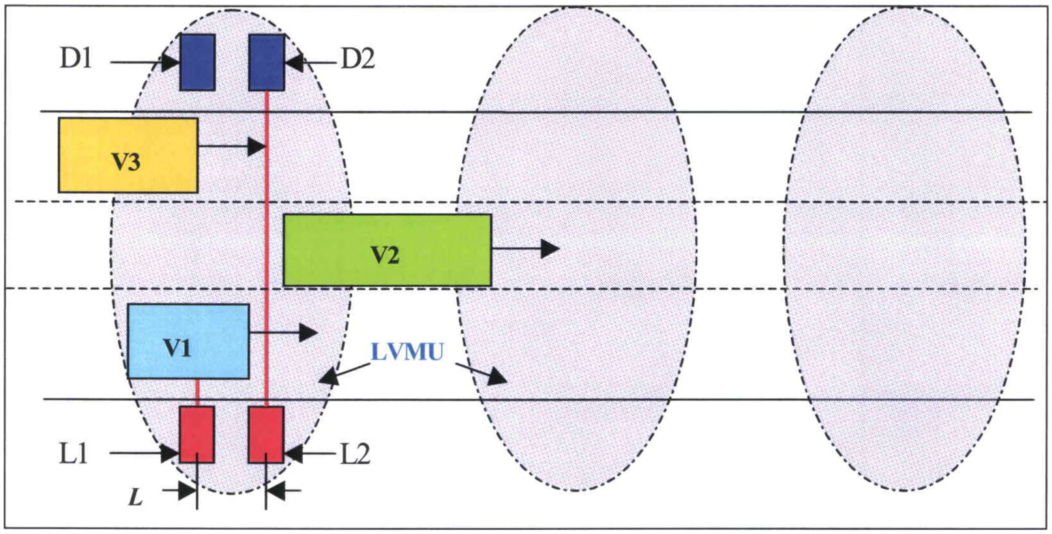


Figure 4: Detection system simultaneous adjacent vehicles

Effectiveness of the design was tested by setting up a model in the lab based on the above theory. Laser diodes as the source of the lasers, photo detector as the detector, model cars/trucks as vehicles and model track as roadway were used to build the prototype. Lasers were low power, on the order of a few milliwatts.

As the light beam from the laser source traverses the highway, it was diffracted. Care was taken to account for this diffraction. To determine the amount of diffraction, the formula for angle of divergence of a laser beam which is $\theta \approx \lambda/\pi\varpi$ was employed. In this formula, λ is the optical wavelength and ϖ is the initial waist [1]of the laser beam. For, ϖ=1mm and λ=1 micron, the angle of divergence, θ was approximately 1 mrad. For a three lane highway with lane width of 10 feet, the formula gave the beam diameter as 3 mm at the detector

[1] The beam waist of a laser beam is the location along the propagation where the beam radius is at minimum.

which was still smaller to the typical detector area (5 mm × 5 mm), and no additional focusing was required.

The effectiveness of the model under inclement weather conditions such as fog, ambient illumination, and smoke was determined by simulating these environmental conditions in the lab. The sensor system was put in a chamber filled with fog created by a fog machine. The system was run to take readings of speed and at the same time the speed was also calculated manually. The probability of failure due to fog was calculated from the number of good estimation and the number of bad estimations.

Fault-tree analysis and modeling was used to evaluate the reliability of the sensors under various conditions and their interactions that might affect its reliability. The paths in the fault tree developed for the sensor identified sequences and relationship between basic events, which led to the top event. The risk was assessed, and based on this result future improvement will be done to reduce the risk of failure of the sensor system.

The top event of a fault-tree was a system failure. By using possible undesired events such as speed data that was not accurate or no speed data, the system was evaluated. All possible events that might led to the top event, such as one laser or detector in a LVMU not working, was evaluated. The system was improved until a threshold minimum failure probability was achieved with the help of iterative procedure. The procedure developed the fault-tree for the system, collected data for all possible events, assessed probability, compared it with the threshold minimum probability and improved the design if the calculated failure probability was higher than the minimum threshold probability, or finalized the system if it equaled or was below the threshold.

Hardware

A laboratory prototype of a sensor was developed. This prototype was constructed of two laser diodes (LD) and two photo detectors (PD) placed across 1 lane. Lane width was 40 cm and the distance between the laser-detector pair was 20 cm. The laser diodes used in this original prototype was a Radio Shack red laser pointer with peak emission at approximately 650 nm while the sharp IS456 photo detector used had peak detection at approximately 650 nm. The data from the sensor was the output from the photo detector to the Rabbit 2000 Microcontroller where the data was processed by the execution of the program written in Dynamic C, a C like language compatible with the Rabbit 2000 processor. The program was uploaded to a Rabbit 2000 processor from a personal computer through its serial interface by using RS-232 protocol. The processed data i.e. the output of the program, then downloaded onto the personal computer through the same RS-232 protocol. A schematic of the first laboratory prototype is shown below in Figure 5.

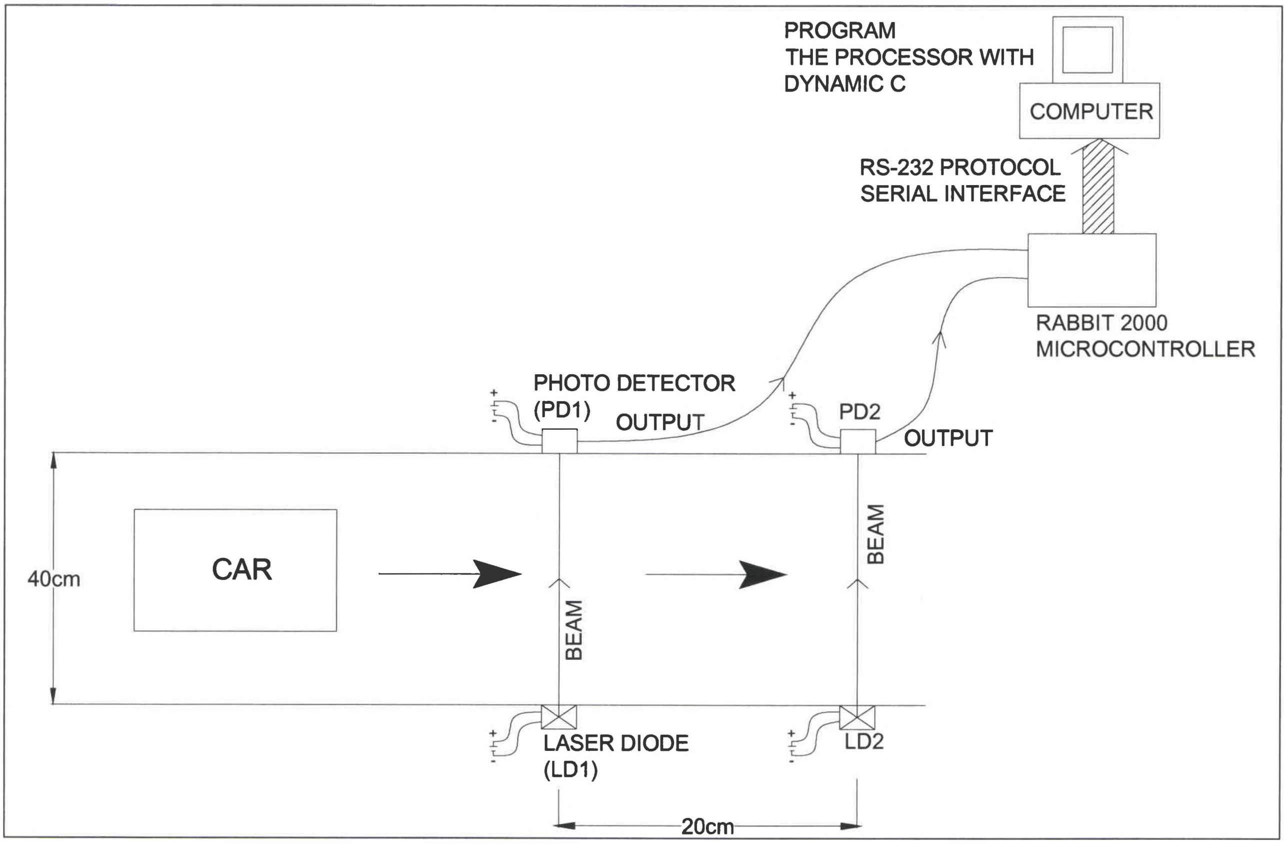


Figure 5: Original laboratory prototype of the transmission-based laser sensor.

As the working prototype could calculate vehicle speeds for one lane of traffic, a sensor system capable of measuring multiple lanes simultaneously was planned. Three laser diodes–photo detector pairs were necessary to build the sensor and also wireless transmitters and a receiver were introduced to more realistically simulate field conditions. The laser diode-photo detector pairs were installed at a distance of 20 cm apart, which was same as the original one. A multiple lane roadway was modeled by using two 40 cm width lanes while keeping the width of each lane the same as the original one. Upgraded laser diodes were Infrared lasers (model NT57116) with a peak emission at 780 nm and upgraded photo detectors were silicon detectors with a peak detection range of 600 nm to 1000 nm.

RF transmitters with a frequency of 900 MHz manufactured by LINX (model TXM-900-HP3-PPS) were connected to the photo diodes. The single RF receivers, also with a frequency equal to 900 MHz and manufactured by LINX (Model RXM-900-HP3-PPS) were then connected to the Rabbit 2000 Microcontroller and channel selector. The microcontroller was connected to a personal computer through the same RS-232 connection as the original one. The schematic of the sensor for multiple lanes is shown in Figure 6.

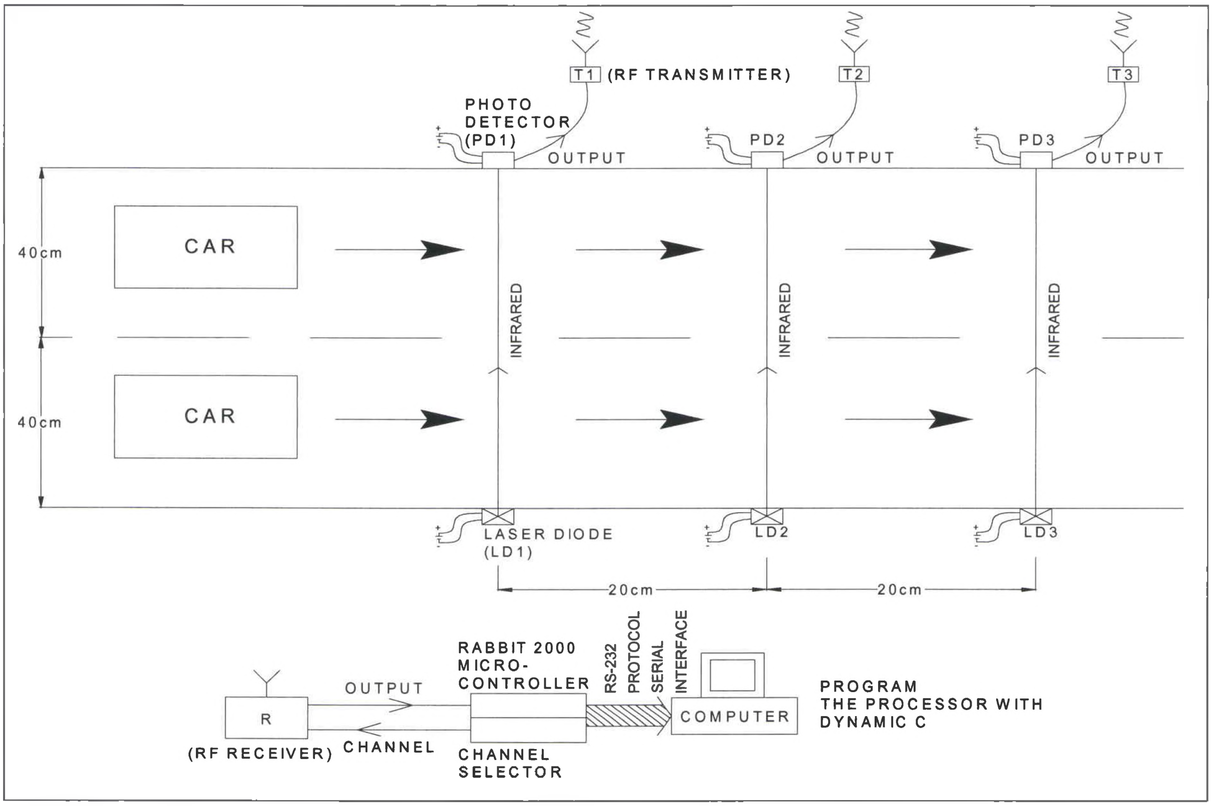


Figure 6: Schematic of the proposed transmission-based laser sensor

The working sensor prototype developed in the lab had two laser diodes (Radio Shack with a peak emission of 650 nm) and two detectors (silicon detectors with peak detection angle of 600 nm to 1000 nm) and the schematic of this is shown in Fig 9. The wireless component of the sensor had been installed, with both the transmitters and the receiver online. Number of vehicles, vehicle's velocity and the size of the vehicles could be measured with good accuracy for one lane only. A two lane stretch of roadway had been already modeled but placement of more laser diodes-photo diodes along with transmitters need to be installed in order to measure speed, count, and size for multiple lanes as described in the methodology. Photographs of the developed sensor prototype and the associated laser diodes and the Rabbit 2000 Microcontroller is shown below in Figure 7 and in Figure 8.

Figure 7: Current transmission-based laser sensor system, as developed in the laboratory.

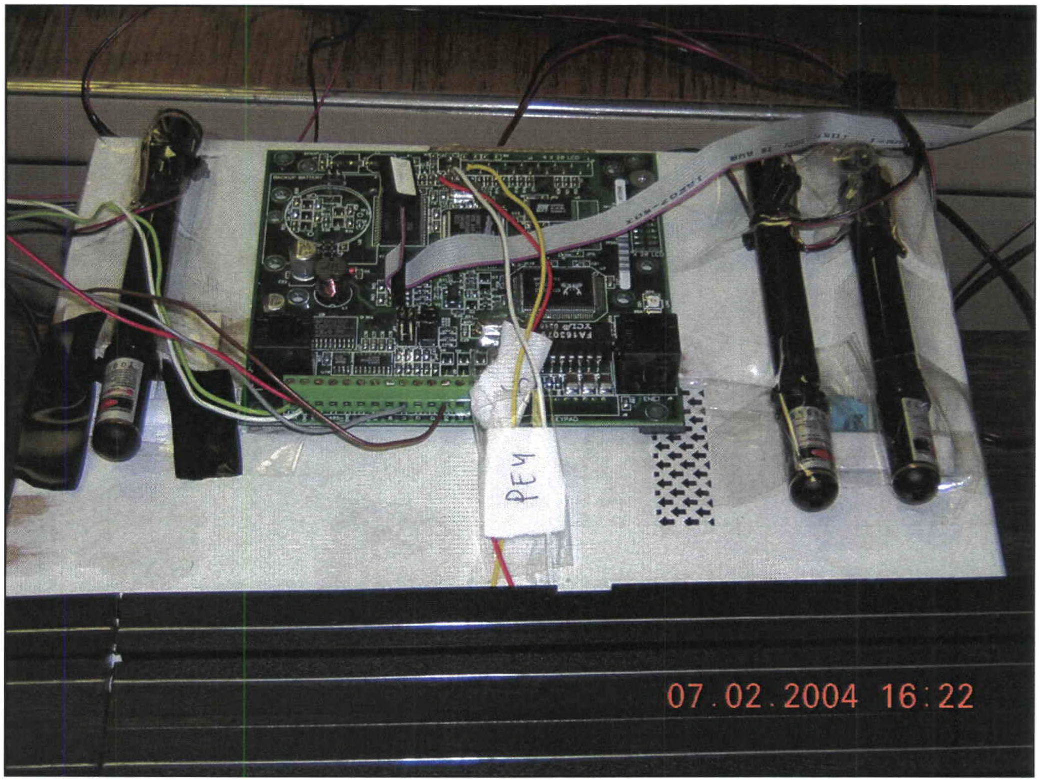


Figure 8: Rabbit 2000 TCP-IP Development Kit and laser diodes

Software

A program was written in Dynamic C to measure the traffic parameters based on the theoretical concept discussed above .It was uploaded from the personal computer through RS232 cable to the Rabbit2000 controller where it was compiled and executed taking the input from the receiver. The output of the program was sent to the personal computer monitor through the same RS232 cable.

CHAPTER III

RISK ANALYSIS OF THE SENSOR SYSTEM USING FAULT-TREE

Development a lab prototype of a transmission based laser sensor was first objective of this research, which has been explained in the previous chapter. This chapter discusses how the sensor system was evaluated. This chapter discusses the issues relating to the procedure of building fault-tree for the sensor, of collecting data related to the events of fault-tree and finally the method to estimate the failure risk of this sensor.

System Definition and Fault Tree Construction for the Sensor

This section describes the developed system from a system analyst point of view and it also describes the steps of fault tree development of the system. The subsection "System Definition" lays out the system's components and their interrelationship while the subsection "Fault Tree Modeling" explains each step of the construction of the fault tree for the developed sensor system.

System Definition

Consider Figure 9 below, which shows the laser-detector system that was developed and tested along with its transmitter, receiver, processor, computer and other electronics.

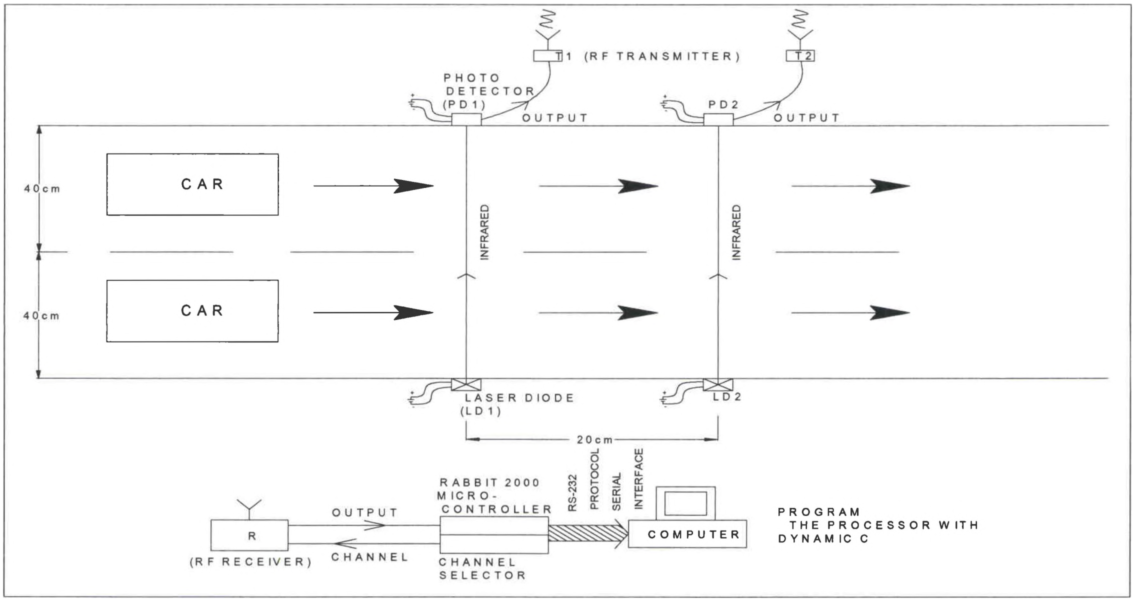


Figure 9: Schematic of the developed transmission-based laser sensor

To make a successful fault-tree for this system the operation of different subsystems, and interaction between different subsystems should be clear. The function of this system was to detect a vehicle and to measure its size and velocity. Whenever a car came in the path of a laser beam the beam could not reach to the detector and detector detected that there was a car. The detector detected the presence of car by identifying a change in the signal. As soon as detector detected the change in signal, the transmitter transmitted the change to the receiver. The two transmitters associated with the two laser-detector pairs sent the signal thorough two different channels and a receiver received the signal from the two transmitters by allocating different time slices to different channels. The Rabbit 2000 microcontroller connected with the receiver performed the task of allocating of time slices to different channels and also it got the information about the presence of the car from the receiver as soon as there was a car in the path of any of the two laser beams. The software program was uploaded from the connected personal computer to the Rabbit 2000 processor where it was complied and executed. The processor got the information of the presence of the vehicle and also the location (i.e. in the path of which laser beam) and it could register the time when this car was detected. With the help of this information the processor could calculate the velocity, size and count in the roadway and these calculated values were sent back to the personal computer for output.

Fault Tree Modeling

The top undesired event was selected as “System Failure After Start”. It was assumed that there was no failure in the wire and the limit of resolution of analysis was set at component failure. Components were those parts of the system shown distinctively in the schematic of the system. To make sure that the top event was written as fault and it specified a “what” and a “when”. Next the test question ”Can this fault consist of component failure?” was applied. The answer was “YES” so an OR-gate was added below the top event and different failure modes of the component failure such as primary, secondary and command modes were considered. In this case however both of the failure modes were secondary mode and the tree was developed as shown in the Figure 10.

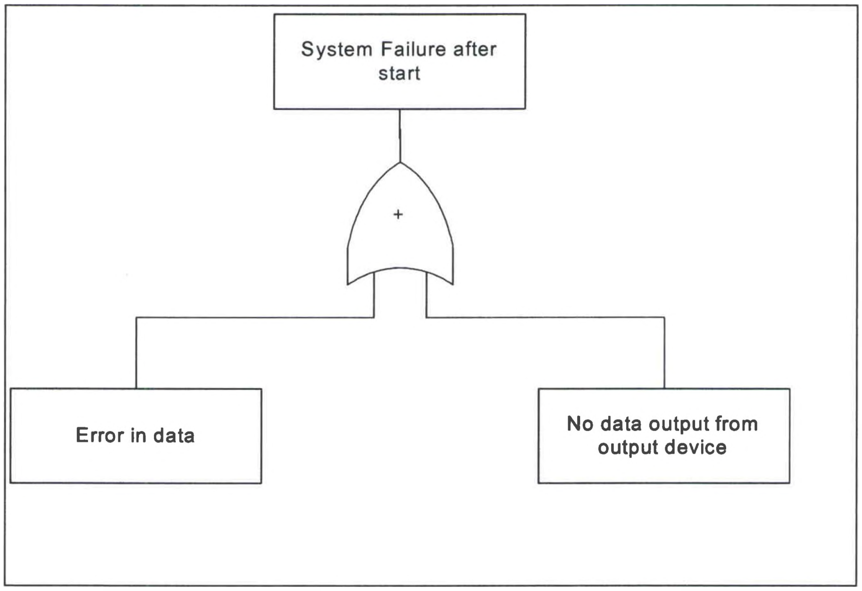


Figure 10: Fault Tree Construction –Step 1

After this, the secondary failure "No data output from output device" was considered and after completing this leg of the tree, the other leg related to the top event "Error in data" was analyzed. Considering "No data output from output device" fault as a component failure an OR-gate was added beneath it and all the inputs to the gate were added. Among the inputs were two undeveloped events, as it was not possible to get data related to these events .The tree assumed the shape as in the Figure 11.

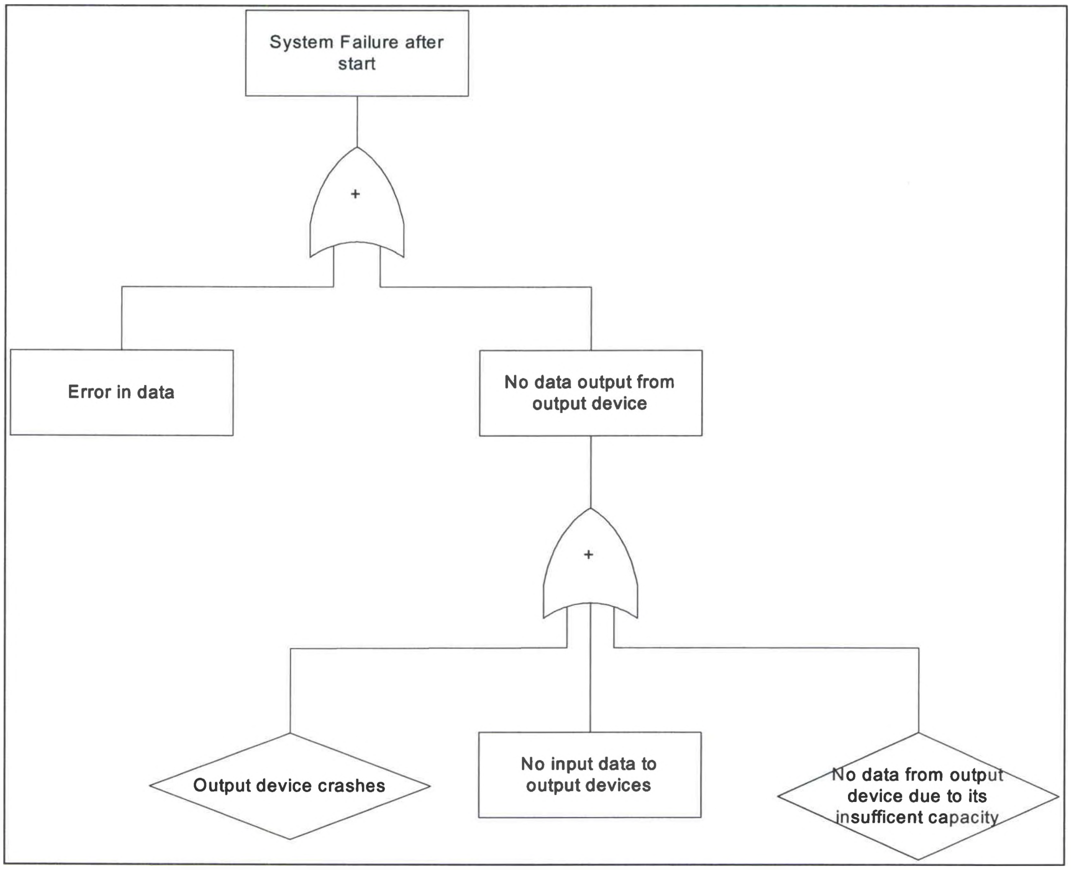


Figure 11: Fault Tree Construction –Step 2

In considering the secondary failure" No input data to output device", this event could take place because of either a "basic event" or a secondary failure both of which were represented as input to an OR-gate that was added below the secondary failure" No input data to output device". The tree so far developed assumed the shape shown in Figure 12.

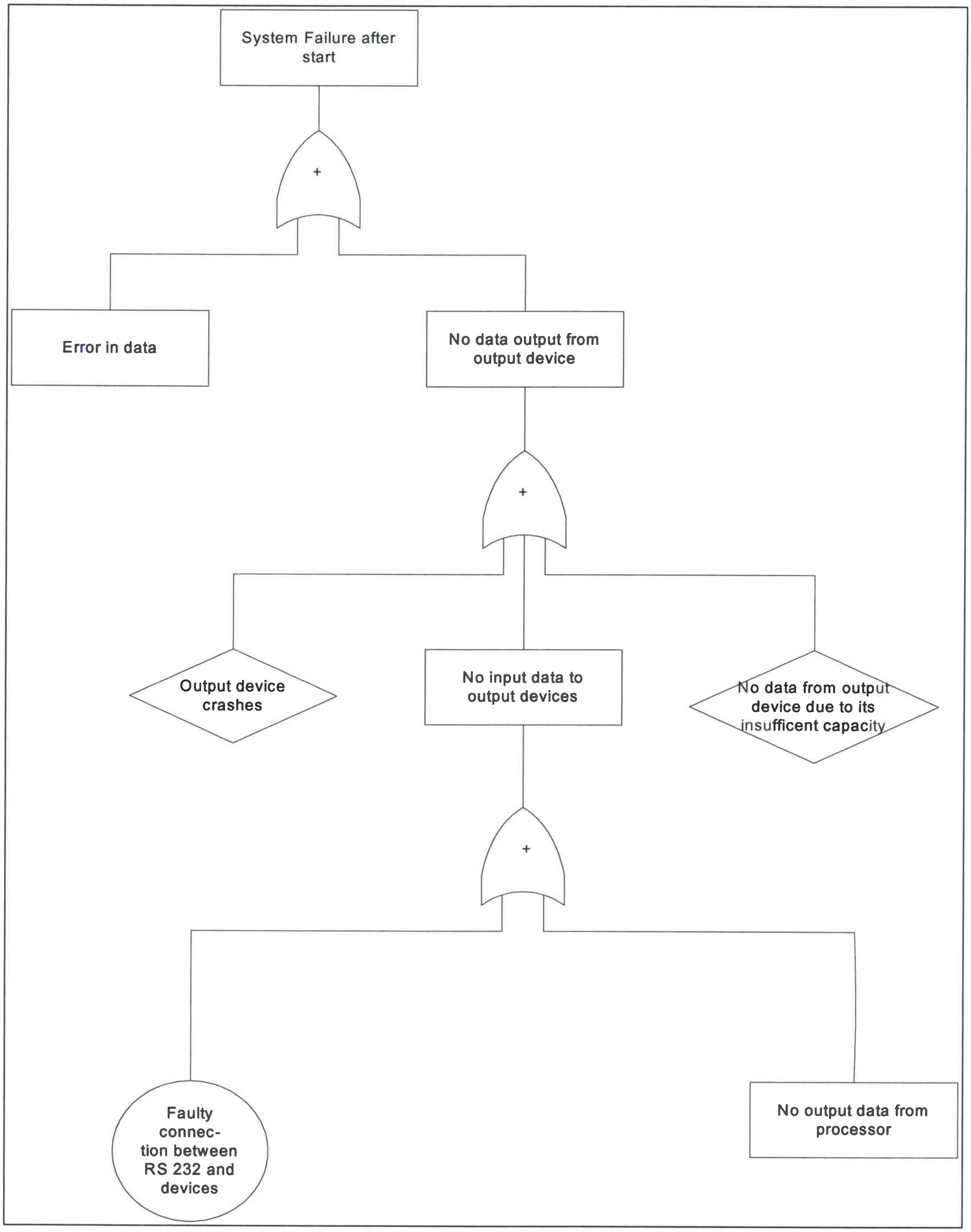


Figure 12: Fault Tree Construction –step 3

From here to the rest of the analysis, for clarity and ease of representation only the event under consideration was shown with its associated gate below it and input events to the gate. The fault event “No output data from processor” could consists of a component failure, so all the input events in Figure 13 were followed by OR-gate.

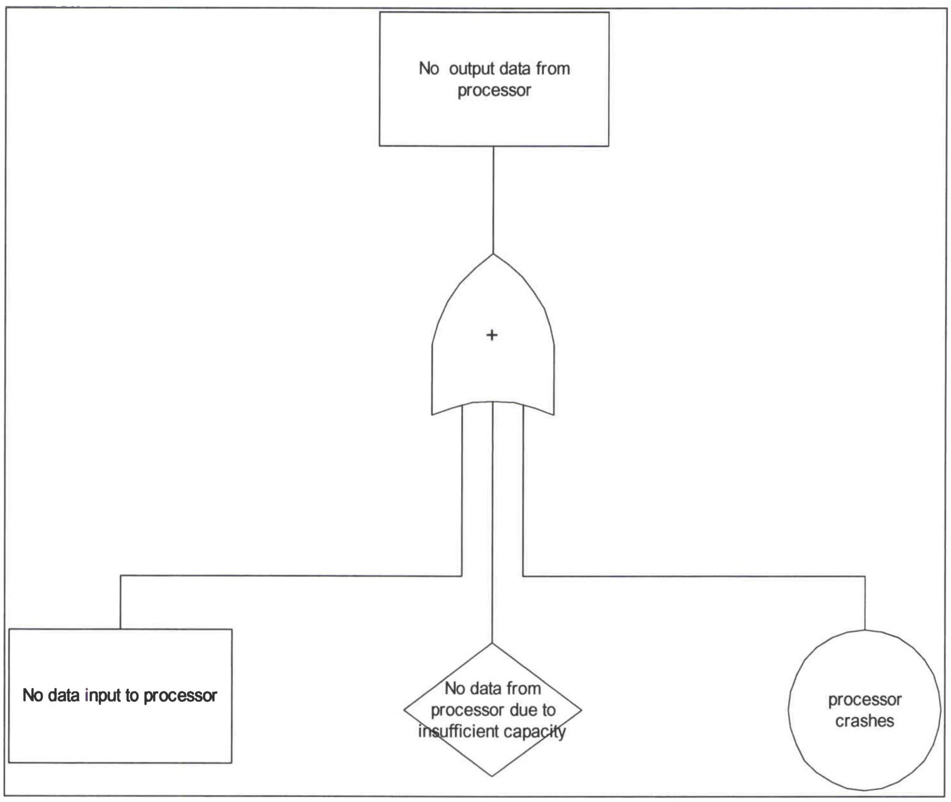


Figure 13: Fault Tree Construction –step 4

The event of interest in this stage was the secondary failure “No data input to processor” (Figure 14). As the top event in this figure could occur due to any one of these input events “No data output from receiver” and “Faulty connection between receiver and processor” an OR-gate was added.

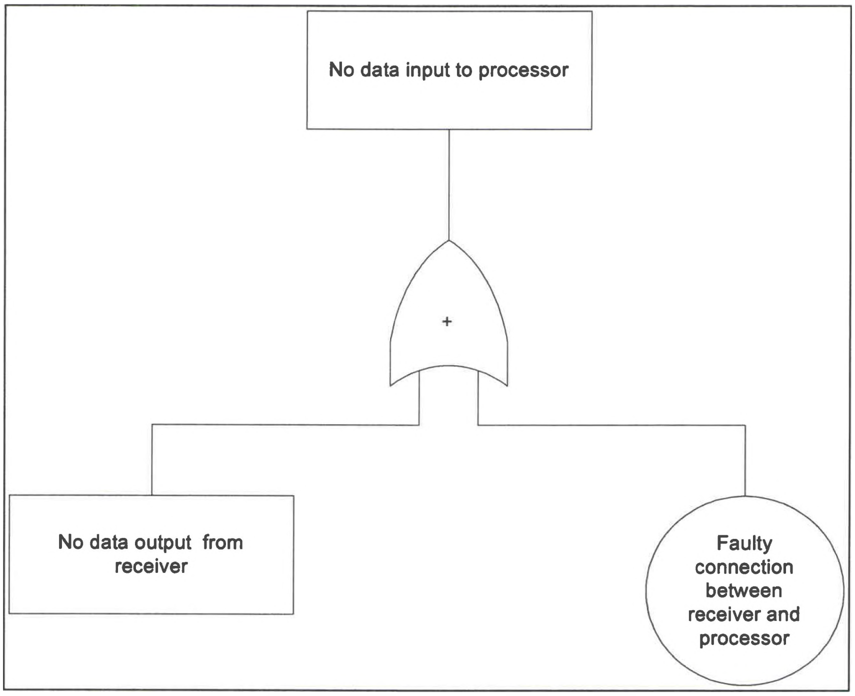


Figure 14: Fault Tree Construction –step 5

Though the reliability of the receiver was high, the chance of failure of receivers was very small but still it could happen; and also if no input data comes to the receiver from the transmitter, then the receiver would not be able to give any data output. These two events were the inputs to the OR-gate added to the top event “No data output from receiver” which was shown in Figure 15.

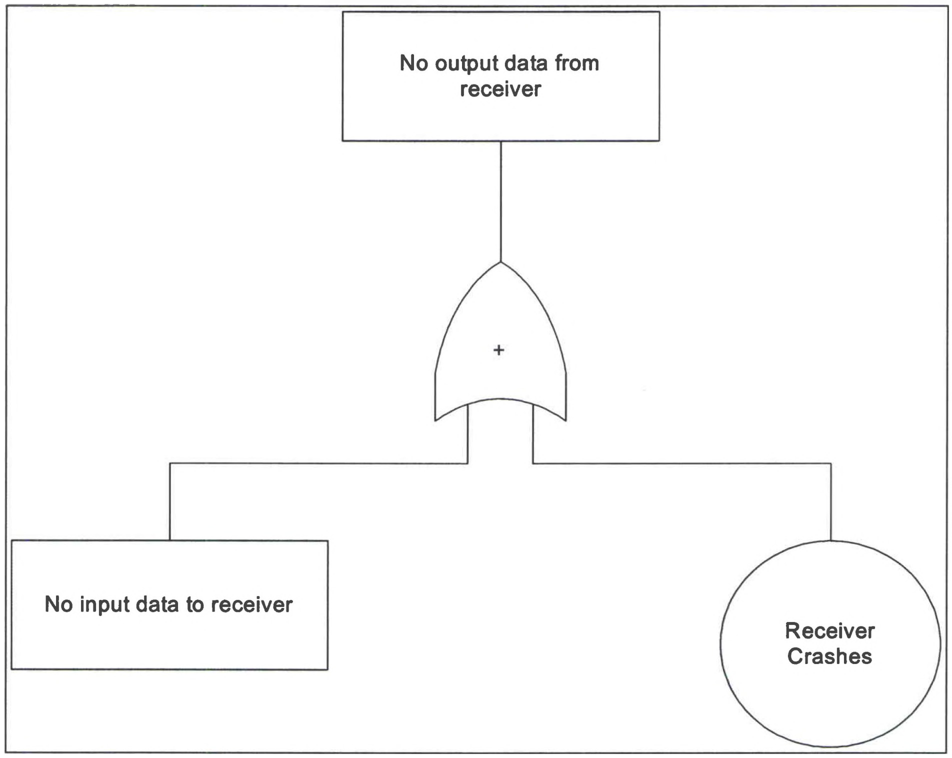


Figure 15: Fault Tree Construction –step 6

Fault event "No input data to receiver" can consist of a component failure, so both the input events in the Figure 16 were followed by OR-gate.

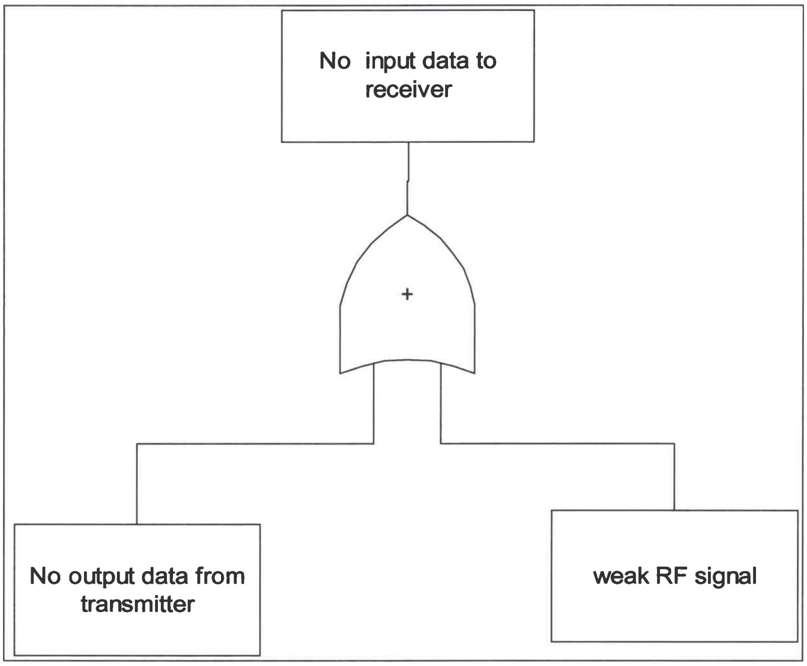


Figure 16: Fault Tree Construction –Step 7

The secondary failure event "No output data from transmitter" was analyzed up to to the point where each of the events was either basic event or undeveloped, then the other secondary failure event "weak RF signal" was analyzed. The transmitter itself could fail though it got data from a detector which could be identified as basic failure event "Transmitter failed", when it did not work under the condition for which it was designed. Also, if the transmitter did not receive any data it would fail, which was defined as secondary failure "No input data to transmitter". These two events were input events to an OR-gate that was added to the top event "No output data from transmitter" (Figure 17).

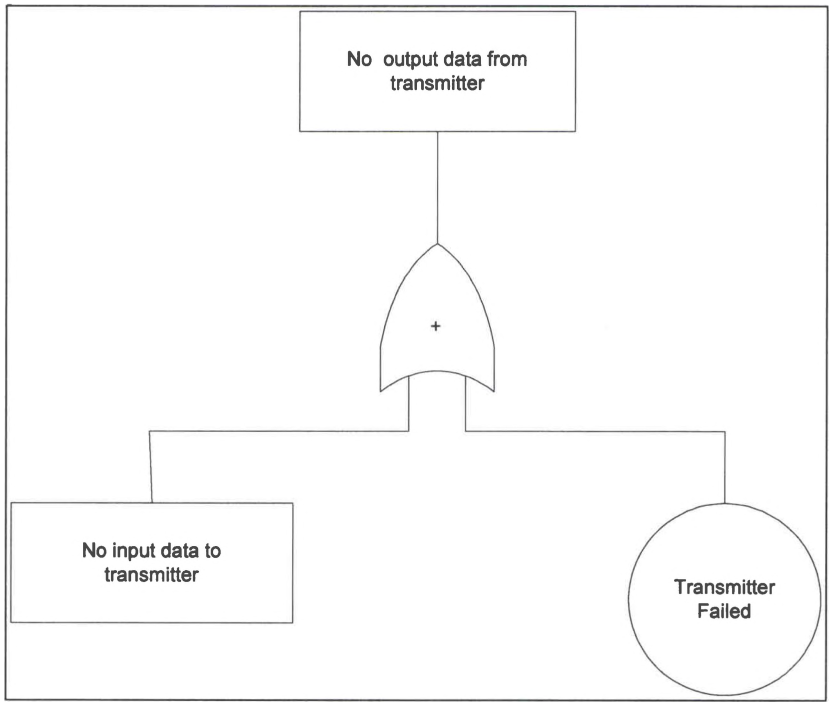


Figure 17: Fault Tree Construction –step 8

In an attempt to analyze the event “No input data to transmitter” it was considered as component failure and consequently the OR-gate with its input events in Figure 18 is shown.

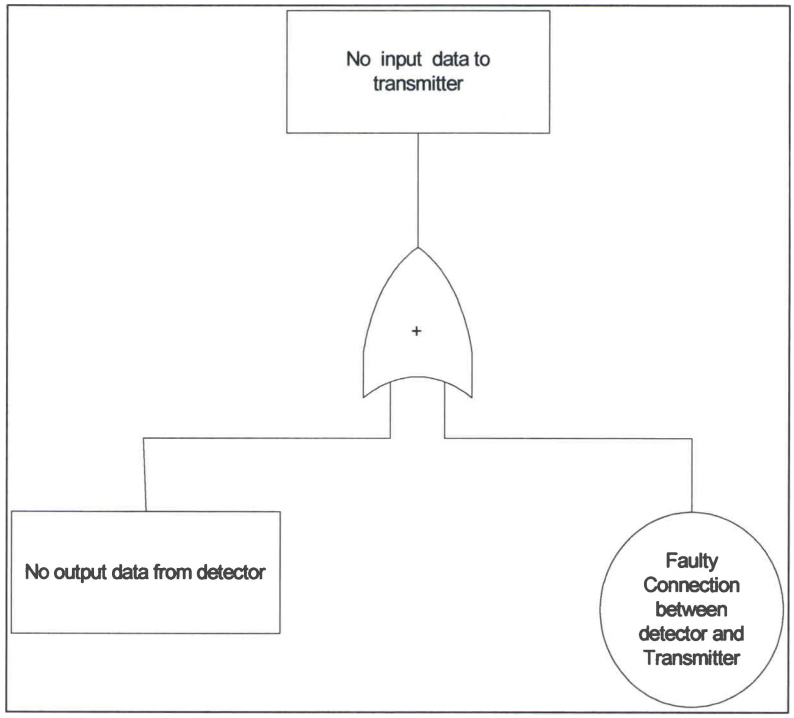


Figure 18: Fault Tree Construction –step 9

“No output data from detector” was a component failure and all of the three inputs were added to an OR-gate as in Figure 19 .Two of these three inputs were secondary failures and they were analyzed separately starting from the left-hand event (Figure 20). Notice that this leg reached the terminus (all events are either circles or diamond), which represented either basic or undeveloped events.

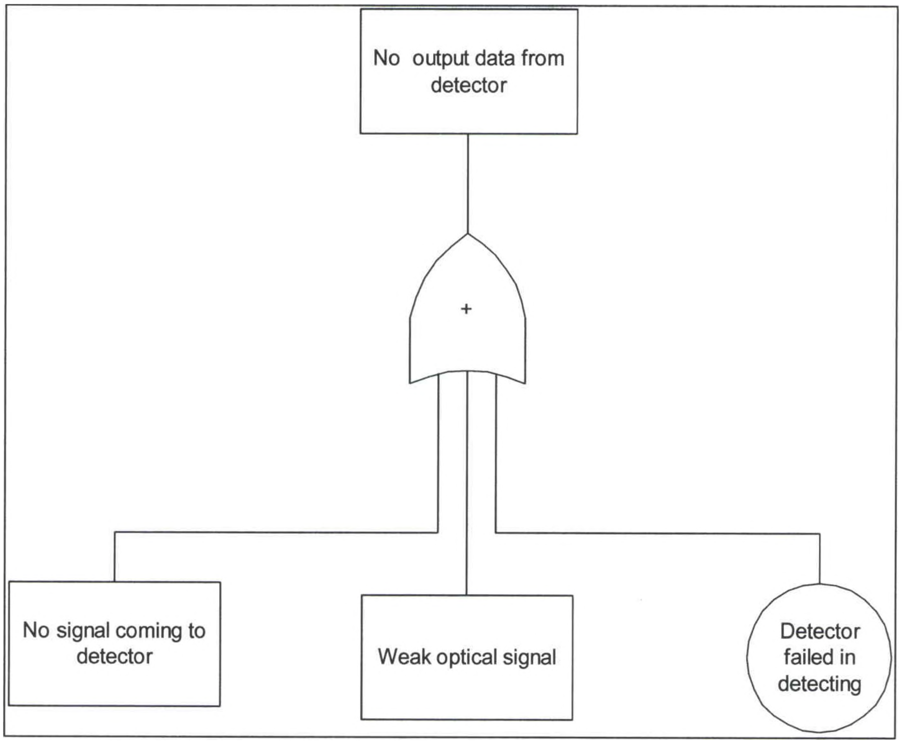


Figure 19: Fault Tree Construction –step 10

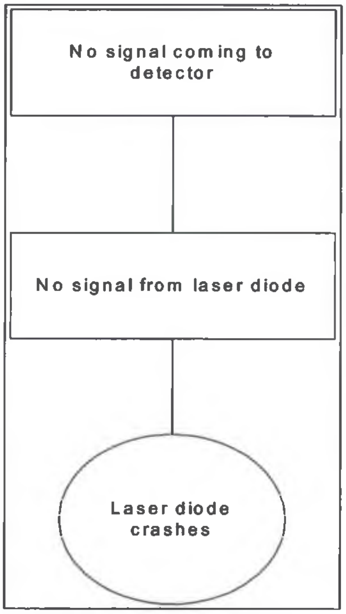


Figure 20: Fault Tree Construction –Step 11

As the middle component failure event "weak optical signal" could happen due to any one of the three inputs two of which were basic events and the third undeveloped, an "OR" gate was added. The signal could be weak in any one of these events due to scattering of beams. Instead of focusing on the detector the scattered beams could focus somewhere else which made the signal weak (Figure 21).

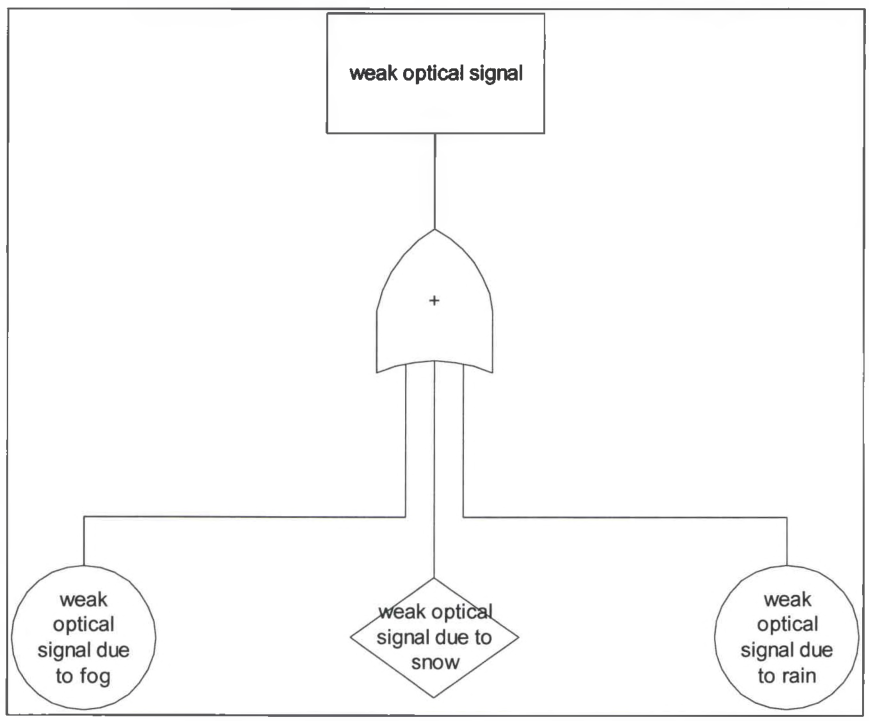


Figure 21: Fault Tree Construction –Step 12

In analyzing the component failure event "weak RF signal", it could happen due to any one of the three inputs two of which were basic events and the third was undeveloped so an "OR" gate was added (Figure 22). This completed the right hand leg of the tree whose top event was "system failure after start". After this the left-leg of this tree is discussed.

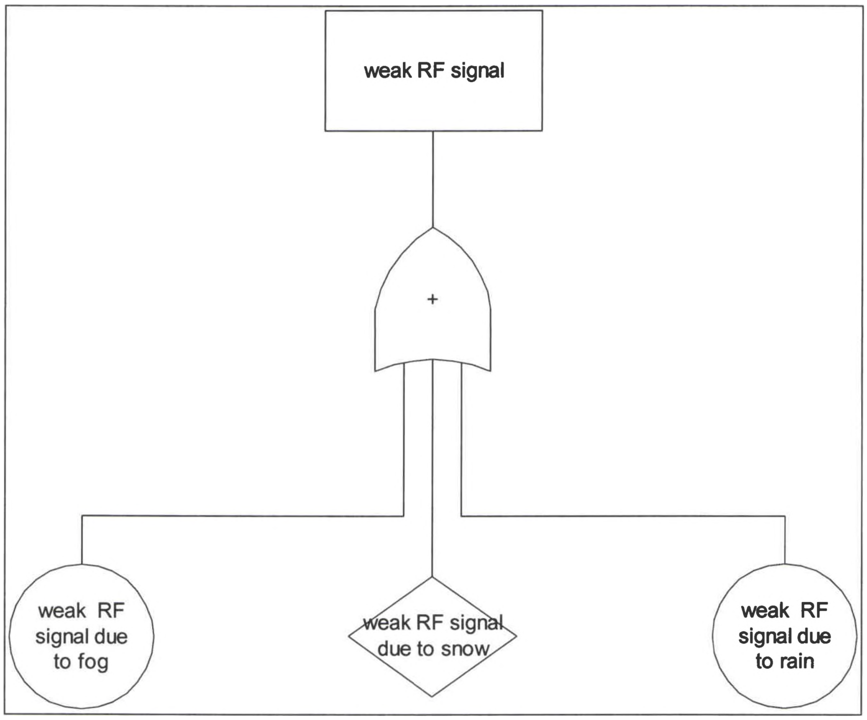


Figure 22: Fault Tree Construction –Step 13

The top event of this leg was " Error in data". As the top event consists of "state-of-system" fault event, an immediate and sufficient cause "Incorrect output from program" was added without adding any gate (Figure 23).

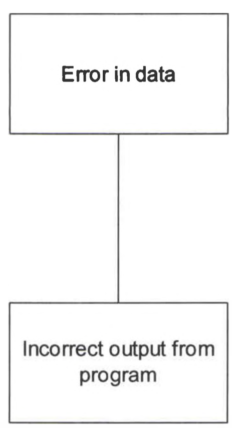


Figure 23: Fault Tree Construction –step 14

The event “Incorrect output from program” was analyzed and as the answer to the question asked to this event “Is this event a component failure” was “YES” an OR-gate with two inputs was added beneath this event in Figure 24.

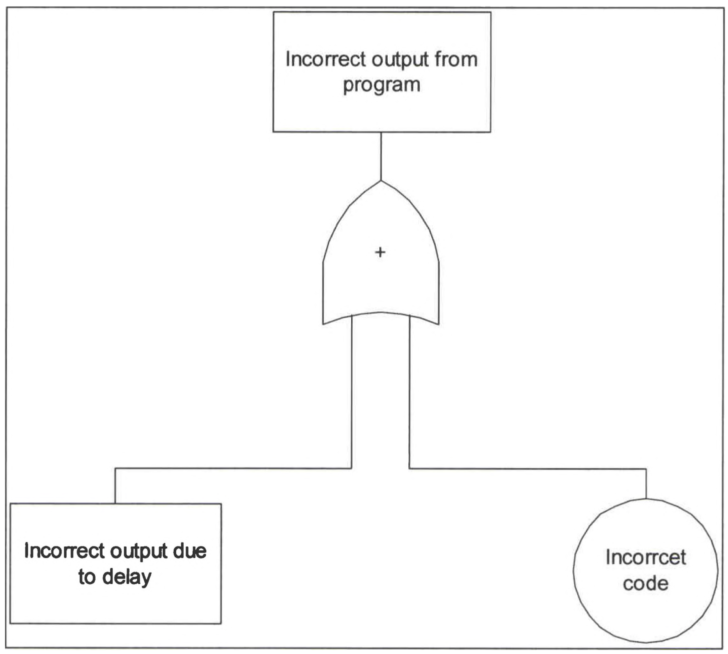


Figure 24: Fault Tree Construction –Step 15

The secondary failure added in could cause incorrect output because of various delays in the program such as delays due to debouncing of beam, channel allocation delay, delays in other electronic devices, and delays which might cause incorrect estimation of time interval between successive blocking of lasers in the system.

As “Incorrect output due to delay” was a state-of-system fault event so the event “Delay in getting data from receiver” was added directly without any gate in Figure 25.

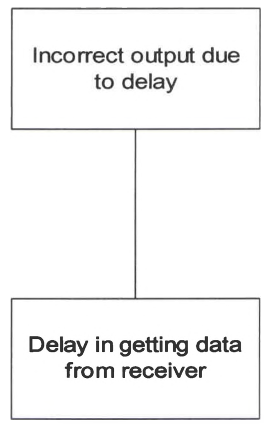


Figure 25: Fault Tree Construction –step 16

“Delay in getting data from receiver” event was a component failure and one undeveloped event with one secondary failure event was added to the OR-gate that was added to the top event in Figure 26 .The event “Delay in receiver sending data to processor” was considered an undeveloped event, as it was not possible to assess the probability of happening of this event exclusively because in a real scenario, delay occurred due to the combinations of several causal factors.

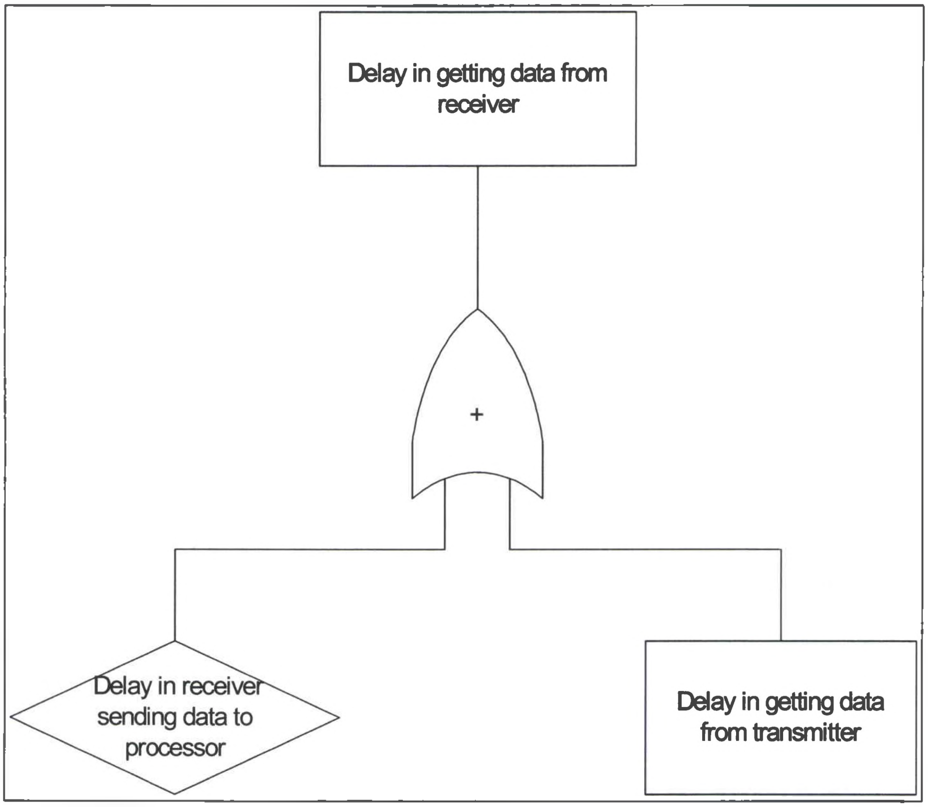


Figure 26: Fault Tree Construction –step 17

The analysis of the event “Delay in getting data from transmitter” up to the point where each of the events was either basic or undeveloped event resulted the tree in the Figure 27, which also completed the tree-building process of the system. In Fig 27 it is seen that all of the leaves consist of undeveloped events, which can be justified because of their inherent interrelatedness and complexity to assess the individual delay due to that event exclusively.

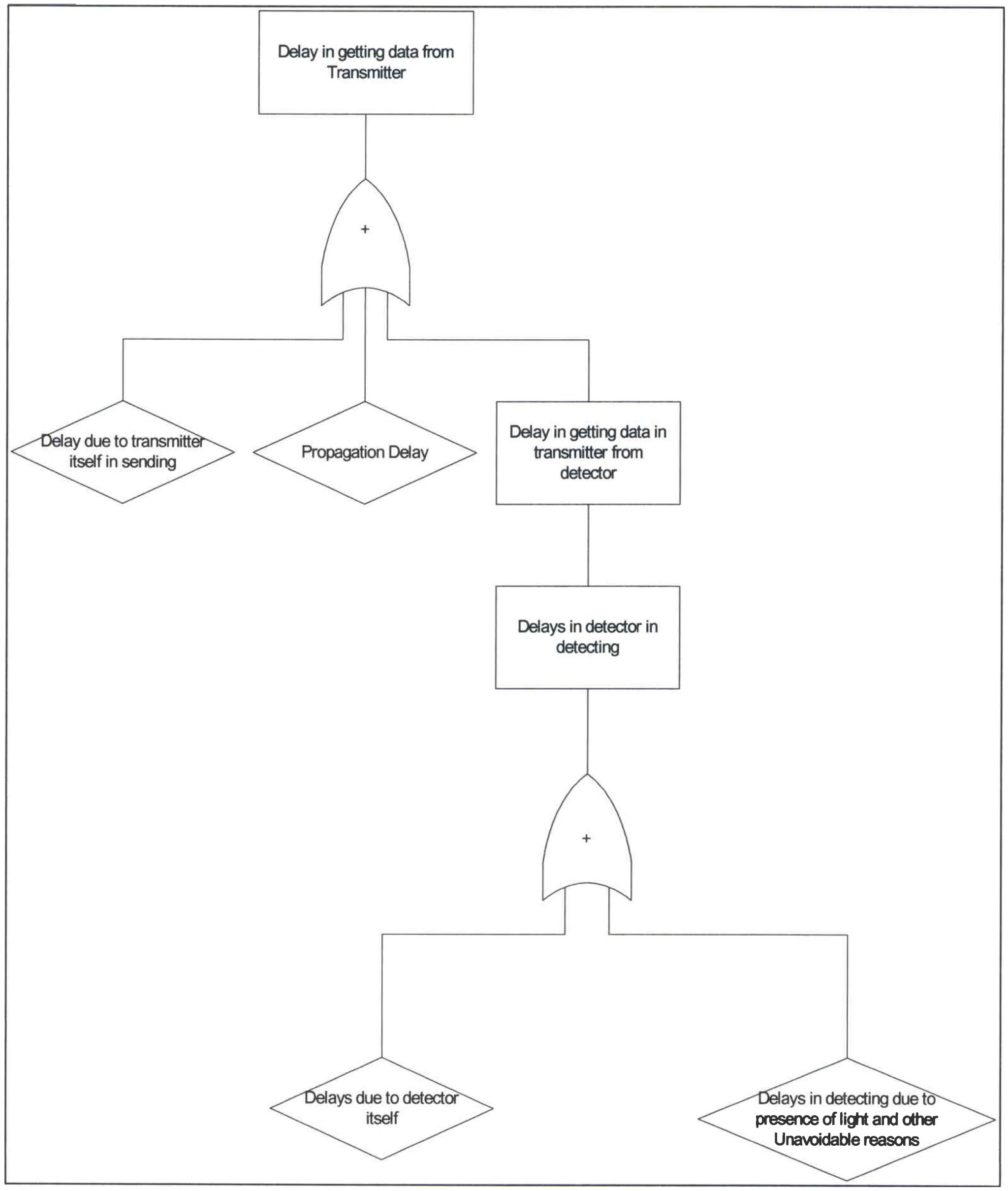


Figure 27: Fault Tree Construction –Step 18

The building of this tree is not explained, as it is straightforward and self-explanatory. Putting all the sub-trees developed in different steps resulted in the complete fault-tree of the system that is shown in the Figure 28.

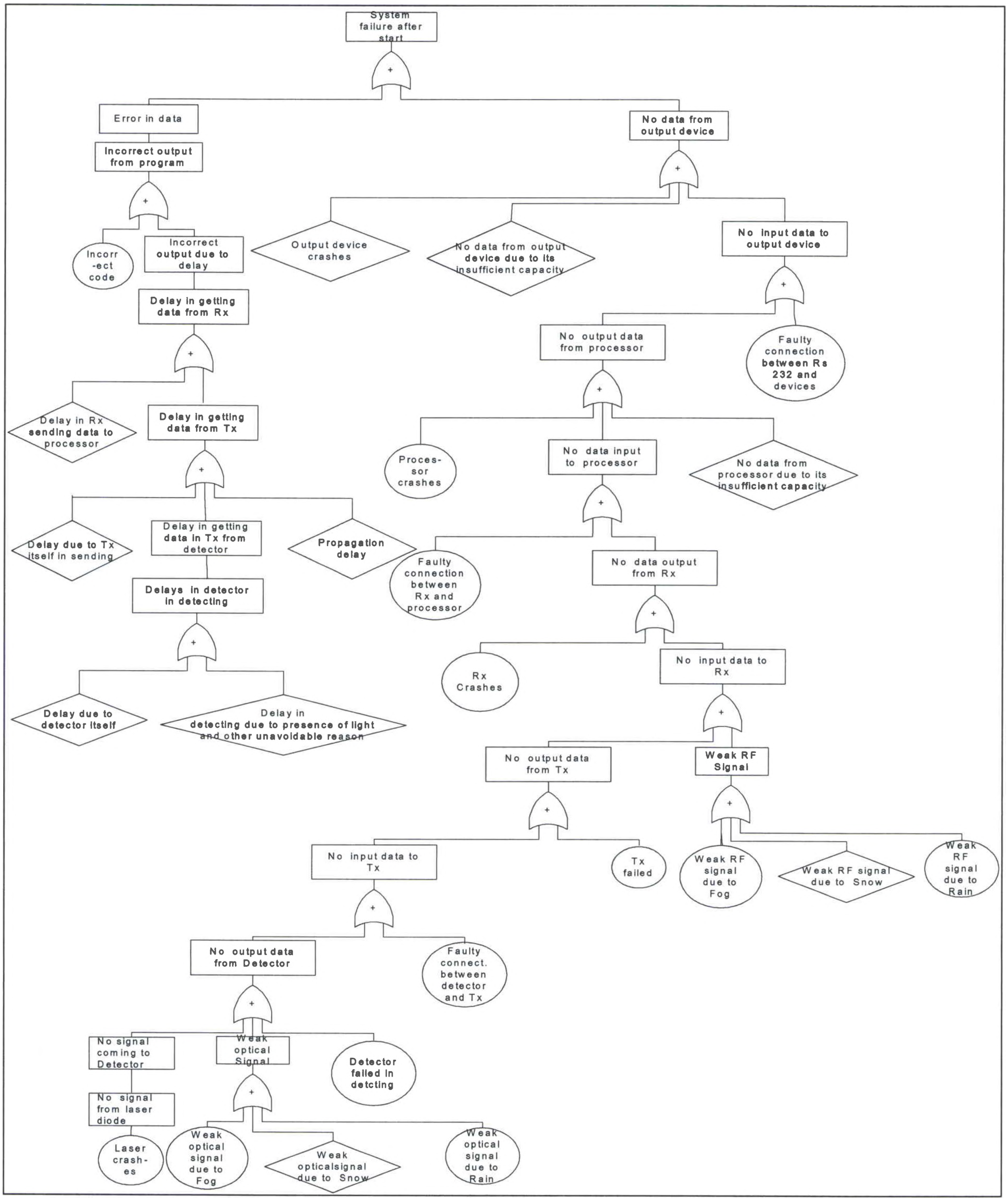


Figure 28: Fault Tree for the System

Data collection for risk analysis

Estimation of the probability of the top event to occur, i.e. the sensor system failure, required the determination of absolute values of the individual component failures. The top event was composed of two types of events explained in the next section. The events were basic events represented by circles and undeveloped events represented by diamonds. The values of undeveloped events could not be assessed as there was not enough information necessary to calculate the values and the values of these events were assumed as zero in this study. The values of primary events were attempted to be calculated. The primary events related to equipments performance characteristics such as the value of P2 or the probability of processor crashes, were collected from the equipment vendor and used directly.

An attempt had been made to collect the data of other primary events in lab, but it was not possible to create exclusively an experimental condition in lab that represents the situation under which the primary event would occur. As an example, to find the failure probability caused by "Weak Signal due to Fog" event, the sensor system was put in a chamber filled with fog created by a fog machine. The system was run to take 100 readings of speed and at the same time the speed was also calculated manually using a stop watch. The probability of failure was calculated from the number of good estimations and the number of bad estimations but it did not yield a good result because, though an attempt was made to create fog only to calculate this value, there were other lab conditions that also played roles in the systems performance. For this reason the values of these primary events were estimated from the recent studies published in well known journals such as Society of Optical Engineering (SPIE).

Evaluate the fault-tree of the sensor to assess risk of failure

The purpose of creating a fault-tree for a system is to evaluate the system's failure probability. To determine this probability we needed to evaluate the fault-tree of the system. Fault-tree evaluation gave two types of results, qualitative and quantitative. The determination of the minimal cut sets, combinations of which gave the probability of the top event i.e. the ultimate system failure, required the Boolean representation of the tree. The solution of these equations gave the combination of basic failure (circles in the Fault-tree) and undeveloped event (diamonds in Fault-tree), which equals the top event's probability. To complete this task the fault-tree of the system shown in Figure 28 was represented in the reduced form as shown in Figure 29, in which all the primary or basic failures were P, all undeveloped events were S, all intermediate failure events were G and the final top event was T .The solution of the T contained combinations of S and P but no G.

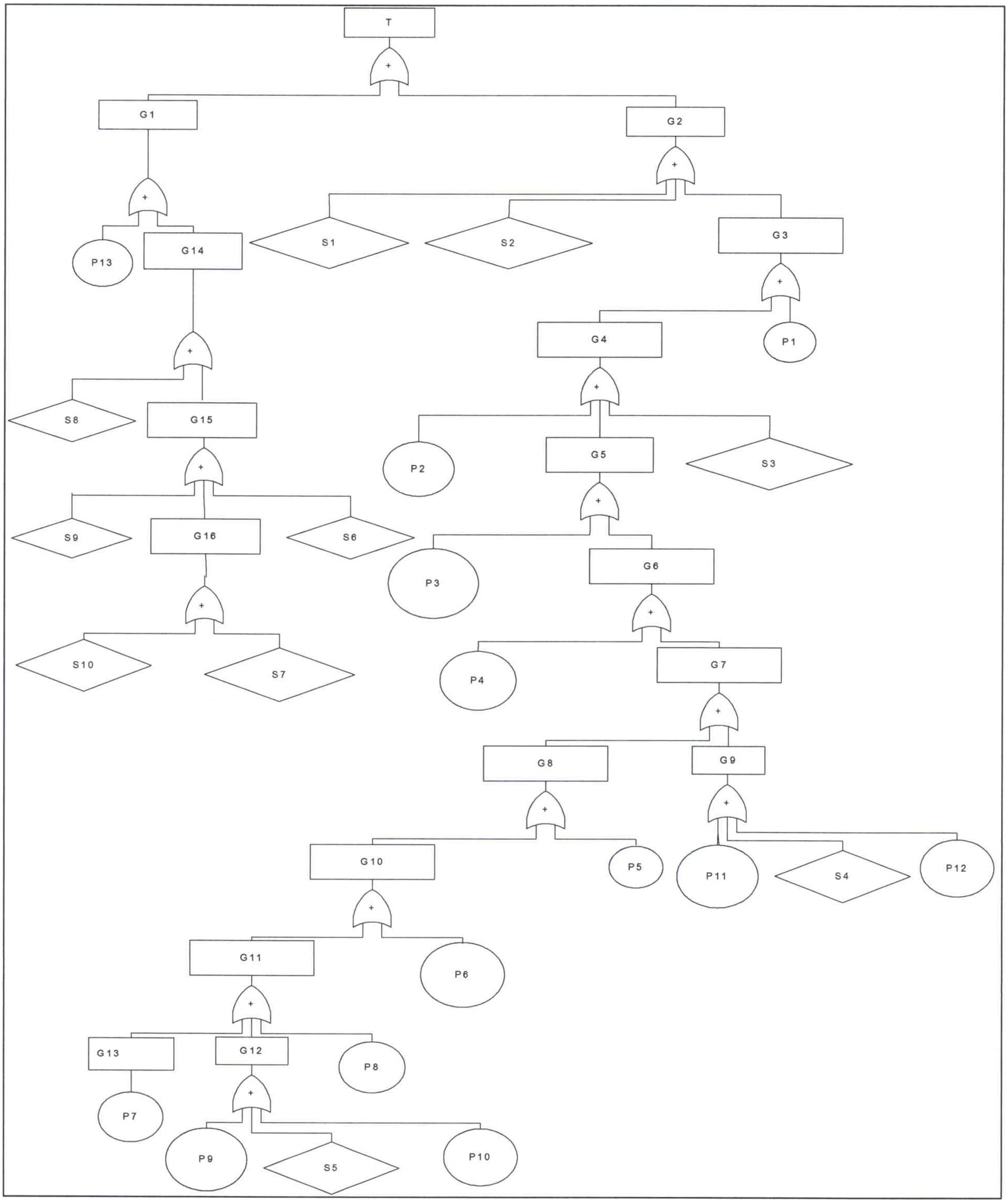


Figure 29: Reduced Fault Tree for the System

Faults

T – System failure (Top event).

G1- Error in data/wrong output from program.

G2 –No data from output device.

G3- No input data to output device.

G4 –No output data from processor.

G5-No data input to processor.

G6 –No data output from receiver.

G7- No input data to receiver.

G8 -No output data from transmitter.

G9 –Weak RF signal.

G10-No input data to transmitter.

G11- No output data from detector.

G12 –Weak optical signal.

G13- No signal coming to detector / No signal from laser diode.

G14 –Wrong output due to delay/ delay in getting data from receiver.

G15 –Delay in getting data from transmitter.

G16-Delays in getting data in transmitter from detector/Delays in detector in detecting.

Undeveloped

S1 – Output device crashes.

S2 – No data from output device due to insufficient capacity.

S3 – No data from processor due to its insufficient capacity.

S4- Weak RF signal due to snow.

S5- Weak optical signal due to snow.

S6 –Propagation delay.

S7 –Delays in detecting due to presence of light and other unavoidable conditions.

S8- Delays in receiver sending data to processor.

S9- Delays due to transmitter itself in sending.

S10 - Delays due to detector itself in detecting.

Primary Event/Basic Event

P1 –Faulty connection between Rs-232 cable and devices.

P2 –Processor crashes.

P3 –Faulty connection between receiver and processor.

P4 –Receiver crashes.

P5 –Transmitter failed.

P6 –Faulty connection between detector and transmitter.

P7 –Laser diode crashes.

P8 –Detector failed in detecting.

P9 – Weak optical signal due to fog.

P10 – Weak optical signal due to rain.

P11 – Weak RF signal due to Fog.

P12 – Weak RF signal due to Rain.

P13 - Incorrect Code.

The equivalent Boolean equations of the tree are as below.

T= G1+ G2

G1=P13+G14; G2=S1+S2+G3

G3=G4+P1; G14=S8+G15

G15=S9+G16+S6; G4=P2+G5+S3

G16=S10+S7; G5=P3+ G6

G6=P4+G7

G7=G8+G9

G8=G10+P5; G9=P11+S4+P12

G10=G11+P6

G11=G13+G12+P8

G12=P9+S5+ P10

Starting with the top event, equation substitutions and expansions had been done for G's until T was expressed in terms of minimal cut sets and the final expression for T was as below.

T=P1+P2+P3+P4+P5+P6+P7+P8+P9+P10+P11+P12+P13+S1+S2+S3+S4+
S5+S6+S7+S8+S9+S10

The values of these individual probabilities were calculated/assumed as follows:

P1 = 0 (Assumed as we tested the connection and then used it).

P2 =0.0001 (Application engineer of the vendor).

P3 =0(Assumed; as we tested the connection and then used it).

P4 =0.0001 (Application engineer of the vendor).

P5=0.0001 (Application engineer of the vendor).

P6 =0(Assumed; as we tested the connection and then used it).

P7 =0.0001(From reference given by vendor of laser diode).

P8=0.0001(From reference given by vendor of laser diode).

P9 =Pr (Weak optical signal due to fog)

In calculating the probability of failure due to weak optical signal due to fog several recent journal papers have been consulted and the following analysis was found. Light propagation thorough atmosphere is affected by absorption and scattering, which is called extinction.

The renowned Beer-Lambert law regarding extinction is:

$\tau(\chi,L) = P(\chi,L)/ P(\chi,0) = \exp[-\gamma(\chi) L]$

Where

$\tau(\chi)$ =total transmittance of the atmosphere at wavelength χ.

$P(\chi,L)$=signal power at a distance L from the transmitter.

$P(\chi,0)$=emitted power.

$\gamma(\chi)$ = attenuation or the total extinction coefficient per unit length.

The extinction coefficient depends upon the particle size distribution of the fog. The extinction coefficient is calculated based on Mie Scattering theoretical model[2].

From this model for 650 nm wavelength optical signal the attenuation coefficient for both the dense advection and radiation fog (visibility 100 m) was found as 40/km.

If the probability of failure is defined as 1- $\tau(\chi,L)$ then Pr (Failure due to weak optical signal in fog) = 1- exp [-(40/100000) *40] =0.015872679

P10 =Pr (Weak optical signal due to rain)

The Beer-Lambert law for atmospheric attenuation or atmospheric transmittance, $\tau_a = e^{-(\beta_{abs} + \beta_{scat}) * R}$ .Where β_{abs} and β_{scat} are the absorption and scattering coefficient respectively. R is the optical depth or the length the optical signal traversed in atmosphere. This is the same equation as before but in different form.

For the infrared spectrum β_{abs} negligible as neither nitrogen nor oxygen which is the most abundant atmospheric gases have any absorption bands[3].

Scattering due to rainfall is wavelength independent as the raindrop size is much larger than the wavelengths causing non-selective scattering. Attenuation due to rainfall depends upon rainfall rate.

In estimating the attenuation due to rainfall a simulation had been done using Simulight software. In this simulation rainfall size distribution was approximated

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2 Maher Al Naboulsi and Fre´de´rique de Fornel,"Fog attenuation prediction for optical and infrared waves", society of optical engineering (SPIE), vol.43 No.2, February 2004.

3 Maha Achour,"Simulating Atmospheric Free-Space Optical Propagation: Part I, Rainfall Attenuation", Proc.SPIE Vol.4635.

by Weibull distribution and a plot of rainfall attenuation vs. rainfall rate had been done [2]. From this plot it was found that for rainfall rate 50 mm/hr (average rainfall rate) attenuation coefficient β_{scat} was 8.25 dB/Km. Putting this value in atmospheric attenuation equation gave τ_a = exp[-8.25 *(40/100000)] =0.9967

Same as before the probability of failure due to weak optical signal in Rain

= 1 - τ_a

=1- 0.9967

= 0.00329

P11= Weak RF signal due to Fog.

Probability of failure due to weak RF signal transmission in Fog was zero, as frequencies below 10GHz were not affected by any weather condition[2].

P12=Weak RF signal due to Rain.

Probability of failure due to weak RF signal transmission in Rain was zero, as frequencies below 10GHz were not affected by any weather condition [2].

P13=0(Assumed as it is tested carefully).

S1=0(No available data).

S2=0(No available data).

S3=0 (No available data).

S4=0(No available data).

S5=0(No available data).

S6=0(No available data).

S7=0(Hard to determine in laboratory due to its interrelationship with other events).

S8=0(Hard to determine in laboratory due to its interrelationship with other events).

S9=0(Hard to determine in laboratory due to its interrelationship with other events).

S10=0(Hard to determine in laboratory due to its interrelationship with other events).

Putting all these values in equation of T the calculated value of

T = 0.0001+0.0001+0.0001+0.0001+0.0001+0.015872679+ 0.00329

=0.019662679

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The developed prototype was tested in lab to measure the performance of the system in adverse weather conditions such as fog or smoke. A fault tree analysis was conducted to calculate the system's failure probability. The researcher attempted to calculate the probability of failure due to each individual primary event by creating the event artificially in lab such as for finding the probability of failure due to the event "Weak Signal due to Fog". The sensor system was put in a chamber filled with fog created by a fog machine. But it was not possible to create an artificial condition for a event that could give the probability of failure due to that event exclusively. As a result the probabilities were estimated from recent studies related to the events. This estimated failure probability of the system is 1.966 % giving the system's availability as 98.034%.

The system design could be improved with more powerful LD and PD pairs. Additional testing under a wide variety of adverse weather conditions such as rain, snow, and fog with representative laboratory setup should be done to assess the system's failure probability and availability.

Recommendations

Based on the analysis the following recommendations were made :

(1) Introduce redundancy in the system i.e. include more microprecessor and transmitter-receiver pairs to make the system robust against component failure.

(2) Use more powerful LD and PD pairs so that the failure probability due to weak signal in adverse weather conditions can be reduced.

(3) Test the system in such a laboratory environment where it would be possible to calculate the failure probability of each event separately.

BIBLIOGRAPHY

Achour, M. “Simulating Atmospheric Free-Space Optical Propagation: Part I, Rainfall Attenuation”. International Society of Optical Engineering, 2002. Proc. of SPIE Vol. 4635.

Cheng,H. H., Shaw, B., Palen, J., Hu, X. D., Larson,J. E. and Katwyk,K. V. "Development and Testing of Field-Deployable Real-Time Laser-Based Non-Intrusive Detection System for Measurement of True Travel Time on the Highway," Research Report UCB-ITS-PRR-2001-6 (2001).

Chowdhury, M., Banerjee, P., Nehmetallah, G., Goodhue, P., Das, A., and Atluri, M. “Development of a reliable transmission-based laser sensor system for Intelligent Transportation Systems”. International Society of Optical Engineering, 2004.

Chowdhury, M. A., and Sadek, A.Fundamentals of Intelligent Transportation Systems Planning. Artech House, 2003. Boston, MA.

Harlow, C. and Peng, S. Vehicle Identification and Classification System with Range Sensors. Louisiana Transportation Research Center. 1997.

ITE journal, Standard news, July 2004.

Klein, L. A. Sensor Technologies and Data Requirements for ITS. Artech House, 2001. Boston, MA.

Maher, A. N., Fre´de´rique de F.,”Fog attenuation prediction for optical and infrared waves”, Society of Optical Engineering (SPIE), vol.43 No.2, February 2004.

Maher, A.N., Herve, S., and Frederique, d.F. “Wavelength Selection for Free Space Optical Telecommunication Technology.” International Society of Optical Engineering, 2004. Proc. of SPIE Vol. 5465.

Pierce, R.M., Ramaprasad, J. and Eisenberg E. “Optical Attenuation in Fog and Clouds.” International Society of Optical Engineering, 2001. Proc. of SPIE Vol. 4530.

Roess, R.P., Prassas, E.S., and McShane, W.R. Traffic Engineering. 3rd Edition. Pearson Prentice Hall, 2004. Upper Saddle River, NJ.

Sundeen,M. “The Expanding Role of Intelligent Transportation Systems.” National Conference of state legislatures, September 2002.

Texas Transportation Institute. “Urban Mobility Information” http://mobility.tamu.edu

Treiterer, J. “Longitudinal Traffic Control by Infrared Sensing, Remote Sensing For Highway Engineering.” Highway Research Record. 1972.

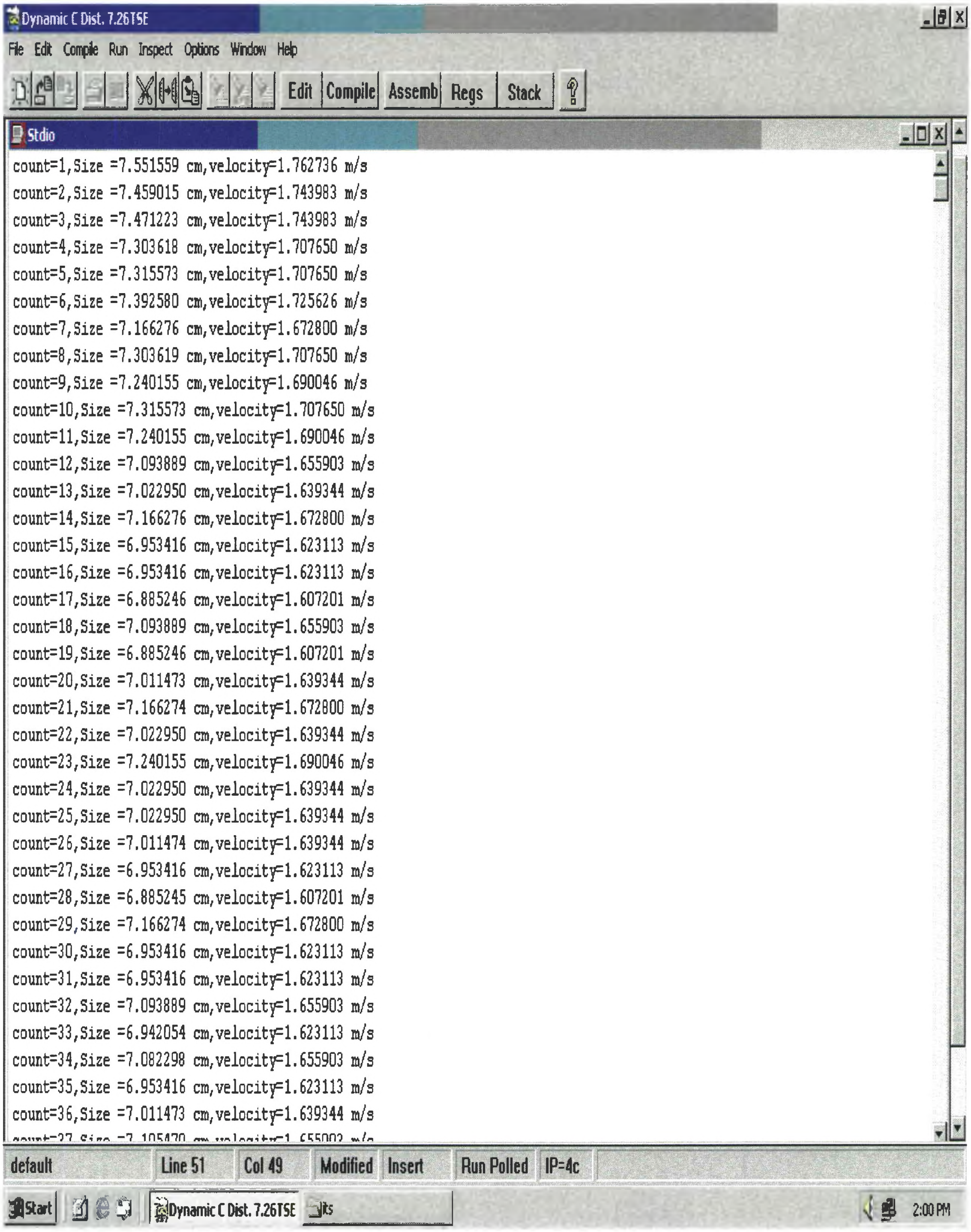
Tropartz, S., Horber E., and Gruner, K. “Experiences and Results from the Vehicle Classification Using Infrared Overhead Laser Sensors at Toll Plazas in New York.” Proc. of IEEE/IEEJ/JSAI International Conference on Intelligent Transportation Systems. Tokyo, Japan: 1999.

APPENDIX A - DYNAMIC 'C' PROGRAM

```
/************************************************************************

 mydemobrd6.c

/*************************************************************************
main(){
  int count1,n;
  float dtime;
  unsigned long StartTime ,EndTime,StartTime2 ,EndTime2;
  float PulseWidth;
   n=0;
  dtime=0;
  count1=0;
  PulseWidth=0;
  // set lowest 2 bits of port D as outputs (o0, o1 on the board)2qx2, the rest as inputs
      WrPortI(PDDDR, &PDDDRShadow, 0x03);
    // set all port D outputs to not be open drain
         WrPortI(PDDCR, &PDDCRShadow, 0x00);
        while (1) {
           while (1) {
            StartTime=0;EndTime=0;PulseWidth=0;
//--------------- prepare to receive the signal from the first photo diode-----------

             BitWrPortI(PDDR, &PDDRShadow, 0x01, 0);    // put CS0=0v or check TR1(led is on)
             if (!BitRdPortI(PDDR, 3))
             break;
            //StartTime = TICK_TIMER;
             while(n<200){n=n+1;}//10 ms delay
             PulseWidth =PulseWidth + n/100;
             n=0;
             if (!BitRdPortI(PDDR, 3))
             break;
//------------- wait for the first detector to stop being interrupted----------------
              while(1){
                      While(BitRdPortI(PDDR, 3)){
                             PulseWidth =PulseWidth + 0.01;
                                       }
                       StartTime2=TICK_TIMER;
                              while(n<200){n=n+1;}//10 ms delay
                               PulseWidth =PulseWidth + n/100;
                                n=0;
                                if (!BitRdPortI(PDDR, 3))
                                 {PulseWidth =PulseWidth - n/100;
                                        break;}
                           }

                           count1=count1+1;
//-------------- prepare to receive the signal from the second photo diode------------

        BitWrPortI(PDDR, &PDDRShadow, 0x00, 0);
        // put CS0=2.7v or check TR2(led is off)
          while(1){
                   while(!BitRdPortI(PDDR, 3));
                        EndTime2= TICK_TIMER;
                        dtime = (float)(EndTime2-StartTime2)*488;
```

```
                while(n<200){n=n+1;}//10 ms delay
                n=0;
               if (BitRdPortI(PDDR, 3))
              {break;}
    }

    printf("count=%d,Size =%f cm,velocity=%f m/s\n",count1,
            PulseWidth*0.6*80000/dtime,80000/dtime);PulseWidth=0;dtime=0;
                    }//end of second while loop
    }  // end of first while loop
}
```

APPENDIX B - OUTPUT FROM A RUN OF THE SENSOR SYSTEM


Dynamic C Dist. 7.26TSE
File Edit Compile Run Inspect Options Window Help
Edit Compile Assemb Regs Stack
Stdio
count=1,Size =7.551559 cm,velocity=1.762736 m/s
count=2,Size =7.459015 cm,velocity=1.743983 m/s
count=3,Size =7.471223 cm,velocity=1.743983 m/s
count=4,Size =7.303618 cm,velocity=1.707650 m/s
count=5,Size =7.315573 cm,velocity=1.707650 m/s
count=6,Size =7.392580 cm,velocity=1.725626 m/s
count=7,Size =7.166276 cm,velocity=1.672800 m/s
count=8,Size =7.303619 cm,velocity=1.707650 m/s
count=9,Size =7.240155 cm,velocity=1.690046 m/s
count=10,Size =7.315573 cm,velocity=1.707650 m/s
count=11,Size =7.240155 cm,velocity=1.690046 m/s
count=12,Size =7.093889 cm,velocity=1.655903 m/s
count=13,Size =7.022950 cm,velocity=1.639344 m/s
count=14,Size =7.166276 cm,velocity=1.672800 m/s
count=15,Size =6.953416 cm,velocity=1.623113 m/s
count=16,Size =6.953416 cm,velocity=1.623113 m/s
count=17,Size =6.885246 cm,velocity=1.607201 m/s
count=18,Size =7.093889 cm,velocity=1.655903 m/s
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count=32,Size =7.093889 cm,velocity=1.655903 m/s
count=33,Size =6.942054 cm,velocity=1.623113 m/s
count=34,Size =7.082298 cm,velocity=1.655903 m/s
count=35,Size =6.953416 cm,velocity=1.623113 m/s
count=36,Size =7.011473 cm,velocity=1.639344 m/s
default Line 51 Col 49 Modified Insert Run Polled IP=4c
Start
Dynamic C Dist. 7.26TSE
2:00 PM