Fault tree analysis of hydraulic power-steering system

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Abstract: The historical development is presented in the introductory part and it points out the importance of using the Fault Tree Analysis (FTA) method for analysis of the reliability and safety of technical systems. By analysing a number of references related to the FTA method, a FTA methodology is established, whose algorithm, with explanation of some steps, is given in this paper. As an example of the practical application of the method, the fault tree of the hydraulic power booster of the steering system of light commercial vehicles is qualitatively analysed. Based on data from the development phase and through a team approach, a fault tree for hydraulic power steering was developed. Along with an explanation of certain parts of the fault tree, the estimation of significance of certain events is done and the possibilities are considered to eliminate causes of failure or to minimise the consequences of failure.

Keywords: reliability; FTA; fault tree analysis; methodology; industrial light vehicle; HPS; hydraulic power-steering system; qualitative analysis.

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1 Introduction

The Fault Tree Analysis – FTA is one of the basic and the most used methods for analysis of technical system reliability and safety. FTA is a deductive method where at first the so-called top event, which in technical systems represents a failure, and then the possible causes of this failure inside the system are analysed. The basis of the fault tree represents a transformation of physical systems to structural logic diagrams.

The FTA method was invented and developed in 1961 by H.A. Watson at Bell Telephone Laboratories in connection with a US Air Force contract for a safety study on the Minuteman Launch Control System (Watson, 1961; Ericson, 1999). After the initial work at Bell Telephone Laboratories, development of the fault tree continued at the Boeing Company, where the technique was applied to manned aircraft and simulation techniques were used extensively. Boeing and AVCO Corporation published fault tree reports on the Minuteman II system in December 1963 (Eckberg, 1963) and January 1964 (Gilmore et al., 1964) respectively. In 1965, D.F. Haasl of the Boeing Company further developed the technique of fault tree construction and its application to a wide variety of industrial safety and reliability problems (Haasl, 1965). In 1965, several papers related to the technique were presented at the System Safety Symposium held at the University of Washington, Seattle (Dhillon, 1999). Boeing in 1966 was the first commercial company that started to use the FTA for the development of commercial aircraft (Begley and Cummings, 1968; Hixenbaugh, 1968). In the seventies, the method was used in particular in the area of nuclear power techniques. In 1974, a conference on "Reliability and Fault Tree Analysis" was held at the University of California, Berkeley (Dhillon, 1999). Three books that described the FTA in considerable depth appeared in 1981 (Roberts et al., 1981; Henley and Kumamoto, 1981; Dhillon and Singh, 1981). From its beginnings until today, the FTA method was used for failure analysis of different technical systems. This method is especially convenient for the reliability and safety analysis of systems whose failures might cause catastrophic consequences for mankind and environment.

The FTA gives the best results in new products designing, because by using this method the potential failure causes are eliminated or reduced to a minimum at the very beginning of the analysis. This method can also be used in the exploitation period for maintenance needs, for diagnostics of causes of failure, for getting feedback on possible modifications of a system and its parts, etc.

Construction and analysis of a fault tree is best performed as a product development team activity. Even though an individual may attempt the FTA, the trees that are developed by a team are generally more fully defined and complete. The reason for this is that a much broader sphere of information is presented and considered by a team.

A motor vehicle's steering system is a mechanical system that has to meet high demands regarding reliability (Lysov, 1972; Janicijevic et al., 1998; Garrett et al., 2001). Together with the braking system and the tyres, it has crucial significance for the safety of motor vehicles and people in traffic (Todorovic, 1988). Steering systems, according to the working principles, can be mechanical, mechanical with hydraulic servo-booster, and hydraulic, while power boosters can be pneumatic, hydraulic or electric. In order to make the steering of heavy vehicles easier, hydraulic power-assisted steering is installed. Hydraulic power-assisted steering is a vital subsystem of the motor vehicle's steering system (Janicijevic et al., 1998). It presents a typical example of a complex device on motor vehicles with a structure conditioned by the complex functions that this device must execute. The importance of the motor vehicle's steering system for human safety requires a detailed analysis of structural components in view of the possibility of occurrence of failure during exploitation.

Practical application of the FTA in the process of product development is illustrated by the FTA of a hydraulic power steering sub-system applied in the steering systems of light commercial vehicles. The hydraulic power steering under consideration is developed by the 'Prva Petoletka' company from Trstenik (Serbia), and is intended to be built into vehicles produced by the 'Zastava Iveco' company from Kragujevac (Serbia).

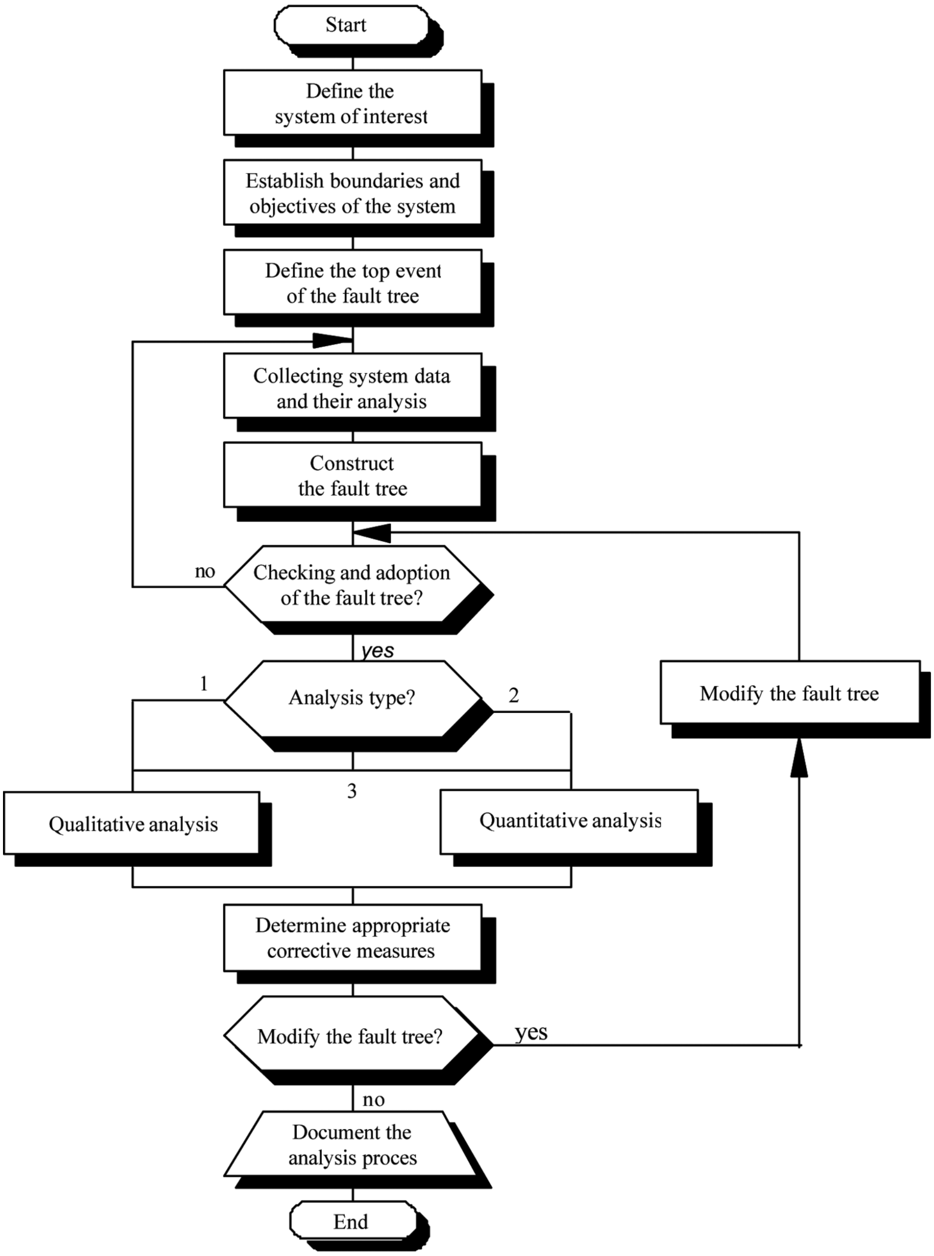
2 Methodology of the fault tree analysis

FTA methodology is described in several industry and government standards, including NRC NUREG–0492 (Roberts et al., 1981) for the nuclear power industry; an aerospace-oriented revision to NUREG–0492 for use by NASA (Vesely et al., 2002); SAE ARP4761 for civil aerospace; MIL–HDBK–338 for military systems and the (7.9 Fault Tree Analysis, 1998) for military systems.

Many different approaches can BE used to model FTAs. Based on the analysis of implementation procedures of the FTA described in the above standards and references starting from (Hixenbaugh, 1968; DeLong, 1970), over (Dhillon, 1985; Lazor, 1995; Dhillon, 1999), to modern literature references from the subject area (Ericson, 2005; Yang, 2007), the FTA methodology is established with the implementation algorithm that is given in Figure 1. According to the given methodology algorithm of the fault tree, analysis comprises the following steps:

- Define the system of interest and any assumptions to be used in the analysis.
- Establish the boundaries and objectives of the system. If it is necessary to simplify the scope of the analysis, develop a simple block diagram of the system, showing input, output and interfaces.
- Define the top event of the fault tree. Depending on the analysed system, it can be general, in the form of a system failure or a specific case involving only a few failures of the system or its components. Careful choice of the top event is very important for the success of the analysis. If the event is too general, then analysis becomes difficult and it cannot be directed. On the other hand, if the event is too specific, analysis does not provide good insight into the system.
- Systematically collect the system data (documentation, calculations, catalogues, service instructions, users' complaints, etc.) and their analyses. It is required that an analyst study the system carefully, considering also the functioning and failure occurrences, before he or she starts constructing the fault tree.
- Construct the fault tree for the established top event. Form the fault tree by using symbols for events, logic gates and transfers. The most commonly used symbols for the formation of the fault tree are given in Table 1 (DeLong, 1970; Barlow, Proschan, 1975; Roberts et al., 1981; Henley and Kumamoto, 1981; Vesely et al., 2002). The power of a fault tree symbolism lies in the fact that the symbols for events, coupled by logic gates, can easily be translated into algebraic expressions.
- Check and adopt the fault tree. If the fault tree does not reflect the real state, or all significant events are not included, or there is no logic relation between the basic and top event, then an additional collection of system data must be performed, as well as a modification of the fault tree. In order to eliminate subjectivity in evaluation of the formed fault tree, the people involved were people who knew well the method used and the research subject, but were not directly involved in the development of the tree.

Figure 1 The algorithm of the methodology of the fault tree analysis



- Carry out qualitative and quantitative analyses. Depending on the final objective of the application of this method, a qualitative or quantitative analysis could be performed when the fault tree was adopted. Determining a set of minimum intersections of events is the basis for most of the fault tree analysis of the quantitative type. The intersection of events is a basic event or a combination of basic events whose occurrence leads to the top event. Among a number of quantitative methods for fault tree analysis, the most commonly used in the practice are the ranking of basic events by structural importance, the ranking of basic events by importance in terms of probabilities of events and determination of appearance probabilities of the top event depending on the appearance probability of basic events (Barlow and Proschan, 1975).

- Determine appropriate corrective measures. Based on obtained and adopted results through the fault tree, one should provide suggestions for corrective measures aimed at eliminating perceived defects or proposals for alternative solutions. Also, decisions have to be made about controlling the manufacturing process or taking risks.
- Any change in the project should be accompanied and verified by an updating of the formed fault tree and related analysis.
- Prepare documentation of the analysis process and follow up on identified corrective measures.

Table 1 Explanations of the constituent symbols of the fault tree

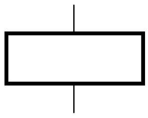
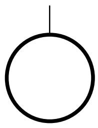
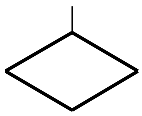
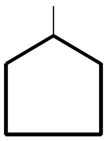
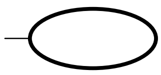
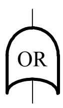
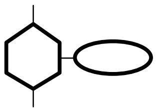
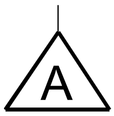
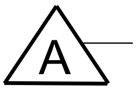
Name of the symbol	*Graphic representation*	*Description*
Top or mediator event		Fault event resulting from the logical combination of the input events, which are operating through the logic gate. It contains description of the event
Primary – basic fault event		Circle to mark a basic initiating fault requiring no further development. Independent event, used only as the input of a logic gate
Secondary – basic fault event (Undeveloped event)		Fault event which is not developed up to its own cause, either because of absence of required information or because the low level of risk, or because of avoiding duplication of the analysis
House event (Normal expected event)		'House' means an expected event that is surely to happen during the normal function of technical system in design work conditions and this event above intermediary one, could be the cause for the top event
Conditioning event		Ellipse to mark a conditioning event. Specific conditions or restrictions that apply to any logic gate (used primarily with PRIORITY AND and INHIBIT gates)
OR gate		Logic gate, which produces output event if one or more of the input events occur. (Output fault occurs if at least one of the input faults occurs.)

Table 1 Explanations of the constituent symbols of the fault tree (continued)

Name of the symbol	*Graphic representation*	*Description*
AND gate		Logic gate, which produces output event if all of the input events occur. (Output fault occurs if all of the input faults occur.)
Inhibit gate		This is used with a conditional event. Input produces output directly only when the conditional input is satisfied.
Transfer in		Indicates that the tree is developed further at the occurrence of the corresponding 'Transfer out' (e.g., on another page). It makes possible avoiding the duplication of identical segments of the fault tree
Transfer out		Indicates that this portion of the tree must be attached at the corresponding 'Transfer in'

In the following basic approach, the development tree, analysis and eventual recommendations for corrective actions are presented as separate steps. In actual practice, there is a great deal of interaction between the steps listed. As a result, the fault tree that evolves includes additions or changes reflecting an improved understanding of the various faults.

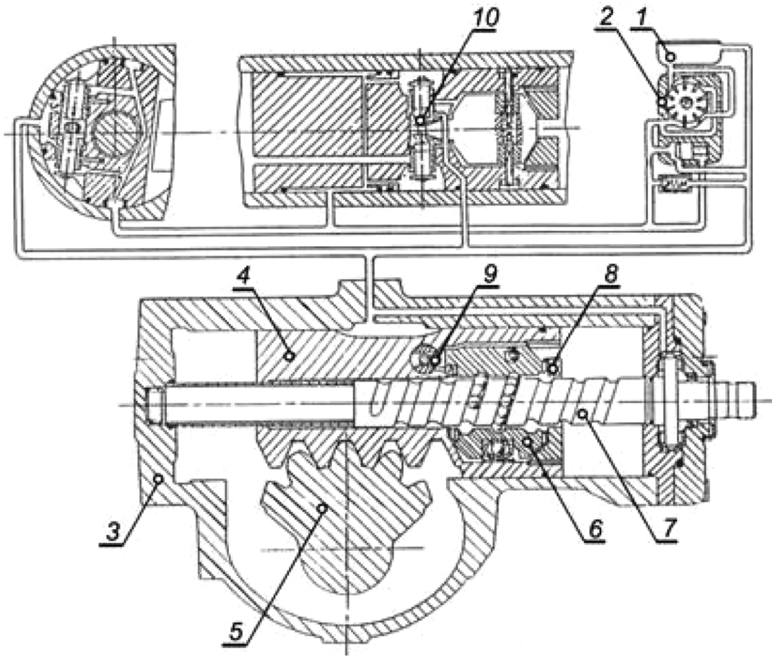
3 Structure and method of operation of designed hydraulic power steering

According to the manufacturer's documentation (documentation on hydraulic power steering), the designed hydraulic power steering for the light commercial vehicle's steering system belongs to the power steering with mechanical connection input-output category. The mechanical steering mechanism, oil distributor and hydraulic cylinder are incorporated in the same housing. A piston valve with axial movement of the operating element is used for oil distribution, which is located within the main piston of the power-steering unit. The advantages of such a solution in relation to the different schemes of structural units are: compact design, minimal amount of piping, quick response of a system and elimination of the possibility that power steering excites oscillations of steering wheels (Janicijevic, 1993; Jörnsen et al., 2001; Heisler, 2002).

According to the way of constructive solution of mechanical parts (Lysov, 1972; Janicijevic et al., 1998), the designed power steering belongs to the combined steering mechanism group, and it consists of a coil with a movable nut and rack with a conical gear segment. This combined power steering is often used in steering systems in motor vehicles, as a purely mechanical unit or as a basis for steering mechanisms with power effect.

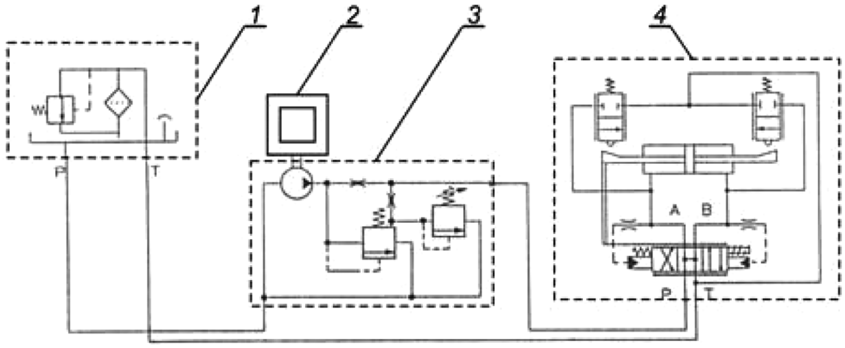
Because of the similarity of conceptual solutions, describing the structure and functioning of the designed hydraulic power steering is shown at the example of power steering ZF type 8045 (ZF-Servocom und ZF-Kugelmutter-Hydrolenkungen, 1992), which applies to vehicles with allowed front axle load of 6500 daN. Figure 2 (ZF-Servocom und ZF-Kugelmutter-Hydrolenkungen, 1992; Hydraulic steering, 1992) shows the typical cross-sections of the hydraulic power steering with the ball-nut type ZF 8045, with an oil reservoir *1* and drive vane pump *2*. In the housing of the hydraulic power steering *3*, which is also the working cylinder, is placed a piston *4* and the toothed segmental shaft *5*. One side of the piston was made in the form of a rack, which is coupled with the segmental shaft, which enables conversion of translator motion of the pistons into the rotating of the segmental shaft, i.e., conversion of fluid stream power energy into mechanical work. There is a nut *6* with a spherical thread in the power booster's piston, which is coupled with the worm shaft *7* via a closed chain of beads. This nut is supported in the piston by two axial needle bearings that unlike the piston, allow its rotation. The axial fixture of the nut in the piston is done by a threaded ring *8*. Rotator *9* is precisely fixed on the nut. During the nut's rotation, the rotor grips the piston of oil distributor *10*, which is placed into the hole on the main piston tangentially relative to the nut.

Figure 2 Scheme of hydraulic power steering ZF type 8045 with tank and vane pump



On the functional hydraulic scheme of the power steering with installation as shown in Figure 3, an oil reservoir with filter and the overflow valve is marked as *1*. The number *2* is marked as the symbol for the drive motor of the vane pump (in this case it is the internal combustion engine). The vane pump, with a valve for restricting flow and pressure, is shown by *3*, and finally, number *4* is the power steering with oil distributor and valves to limit step.

Figure 3 Functional scheme of hydraulic power steering ZF 8045 with the installation



The functional scheme of the hydraulic power steering shows the composition and functioning of the hydraulic circuit. Symbols of hydraulic components are given according to ISO 1219-2 BS, which set the graphic symbols of hydraulic components (BS ISO 1219-2, 1995).

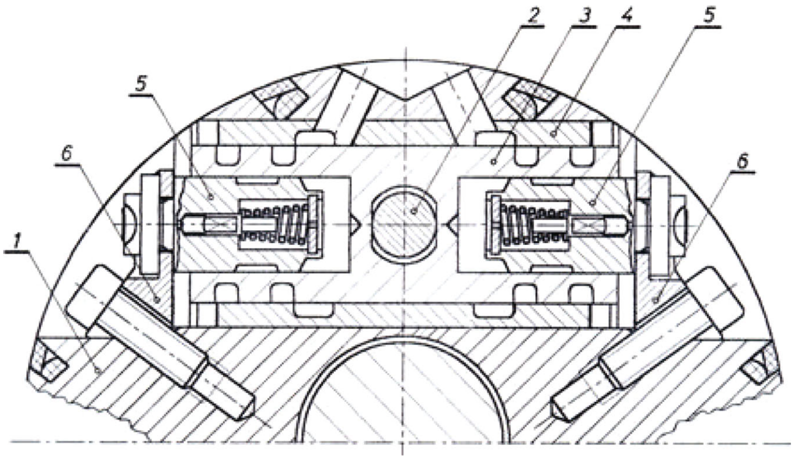
This hydraulic power-steering system for steering the light commercial vehicle operates in the following way. By turning the steering wheel, the torque over the connection elements is transferred to the worm shaft of the power steering. By rotation of the worm shaft, the force is transferred over the 'travelling' ball bearings to the nut of the steering wheel. The force can be resolved into axial and tangential components. The axial component of the force on the nut is transferred to the piston and causes its movement in the direction of the force. The tangential component of the force causes rotation of the nut, which is transferred by the rotor to the nut, and the distributor's piston is moved from the neutral position. This force opposes the force resulting from the pistons with retroactive action, which tends to return the nut to the starting position.

Figure 4 shows a cross-section of the power steering's distributor ZF 8045. Number *1* marks the power steering's piston containing a nut with attached rotator marked with the number *2*. The working element of the distributor is a cylindrical piston *3* with frontal openings, annular grooves and belts. Axial displacement of the piston is carried out in a distributor's capsule *4*, where they made openings for supply and drain of fluid. Within the distributor's piston is placed pistons with retroactive effect *5*, who through the corresponding brackets *6* are attached to the power steering's piston.

In the neutral position of the distributor's piston, the oil flows from the pump through the commanding edges of the outside and inside grooves of the distributor's piston and the tolerated gap between the distributor's piston and capsule, to the return line of hydraulic installation. There is the same pressure in both chambers of the hydraulic cylinder, so that the power steering's piston and segment shaft are in the equilibrium state. There is certain fall in pressure in the casing's chambers – pressure damping, which acts on both sides of the piston and which has the function of stabilising the system. This pressure, with a value of about 5 bars, is realised by the appropriate position of the commanding edges of the external and internal grooves, the tolerance gap between the distributor's piston and capsule and the centred position of the distributor. By an axial displacement of the distributor's piston, regulation openings for the connection of the hydraulic cylinder's chambers with pushdown and return line are expanding and narrowing. By moving the piston for a few hundredths parts of a millimetre the connection between the chamber into which oil is going and return line is broken.

At the same time, the opening for connection between another chamber and return line is expanded and oil from that chamber of the working cylinder flows through the return line to the reservoir. That allows an increase of oil pressure on the appropriate side of the piston, its movement and overcoming of load.

Figure 4 Cross-section of the power steering's distributor ZF 8045



In short, turning the steering wheel activates the hydraulic power booster's distributor, which, depending on the rotation direction of the steering wheel, transfers the oil into one or the other chamber. The position of the distributor's piston determines the oil pressure in the system and the action direction of the power booster's piston. The pressure increases in the chamber into which the oil is transferred and starts the motion of the piston, which through its teeth turns the shaft segment. The power booster's piston moves under the action of hydraulic force until the driver turns the steering wheel, i.e., while acting on the distributor's piston. After the termination of the steering wheel rotation, distributor's piston occupies its neutral position and the pressure in both chambers is equalised.

If the hydraulic action was maximal also in extreme positions of the turned wheels, that would result in unnecessary overload and damage of the power steering components and the Ackerman linkage of the steering system. Abruptly stopping of the fluid flow causes mechanical and hydraulic shocks. Therefore, almost all motor vehicles with hydraulic power steering have a mechanical limiter for hydraulic limitation of final position of turnaround wheels. In the power steering ZF type 8045, hydraulic restriction of the power-steering lever's travel is performed by two valves installed in the cover of the power booster's housing. Activation of the valve is done mechanically through the cam (limiter) at the free end of the segment shaft, which raises the valve piston, thereby overcoming bias of a spring in the valve. During operation, the power steering's valves remain closed until reaching the limit position, or until the cam of the segment shaft does not open one of the valves. By opening the valve, the chamber under the pressure is connected to the return line to the reservoir. Steering wheel can still rotate in the same direction, only with the use of much larger forces by hands.

4 Formation and analysis of the fault tree of hydraulic power steering

In addition to our own conclusions on the object of investigation, in the process of formation of the fault tree, we consulted experts in the research, production, testing and maintenance of hydraulic power steering. For recording of potential failures, in addition to manufacturer's instructions for maintenance and control checks of the power steering (ZF-Servocom und ZF-Kugelmutter-Hydrolenkungen, 1992; Hydraulic steering, 1992), the book (Savic, 1997) was used where problems in the working of hydraulic devices and diagnostic procedures for failure causes are described in detail.

In order to get detailed knowledge of the structure of a hydraulic power-steering system with installation, based on design documentation of the manufacturer (documentation on hydraulic power steering), a structural block diagram of the observed object was formed. As it can be seen from Figure 5, structural parts of hydraulic power steering are divided into five different structural levels. Hydraulic installation and the power-steering system are marked as subsystem components because they are at higher structural levels than subassemblies and, at the same time, they are constituents of the subsystem. Empty fields, bordered by dashed lines in Figure 5, represent that the corresponding structural units contain many parts that were omitted due to lack of space in the picture.

Depending on the ways of classifying the top event basic causes and ways of defining sub-top events, there are three ways of forming the fault tree. In the first case, the mediator events in the fault tree are states of the corresponding structural units (a hardware approach); in the second are events that describe the way in which the failure occurred and that are common to several elements, regardless of the structural origin (functional approach). The third option combines the previous two. The first way is more convenient for forming a block-scheme of reliability and for Failure Mode and Effects Analysis (FMEA). The second way is more convenient for analysis of failures' common cause.

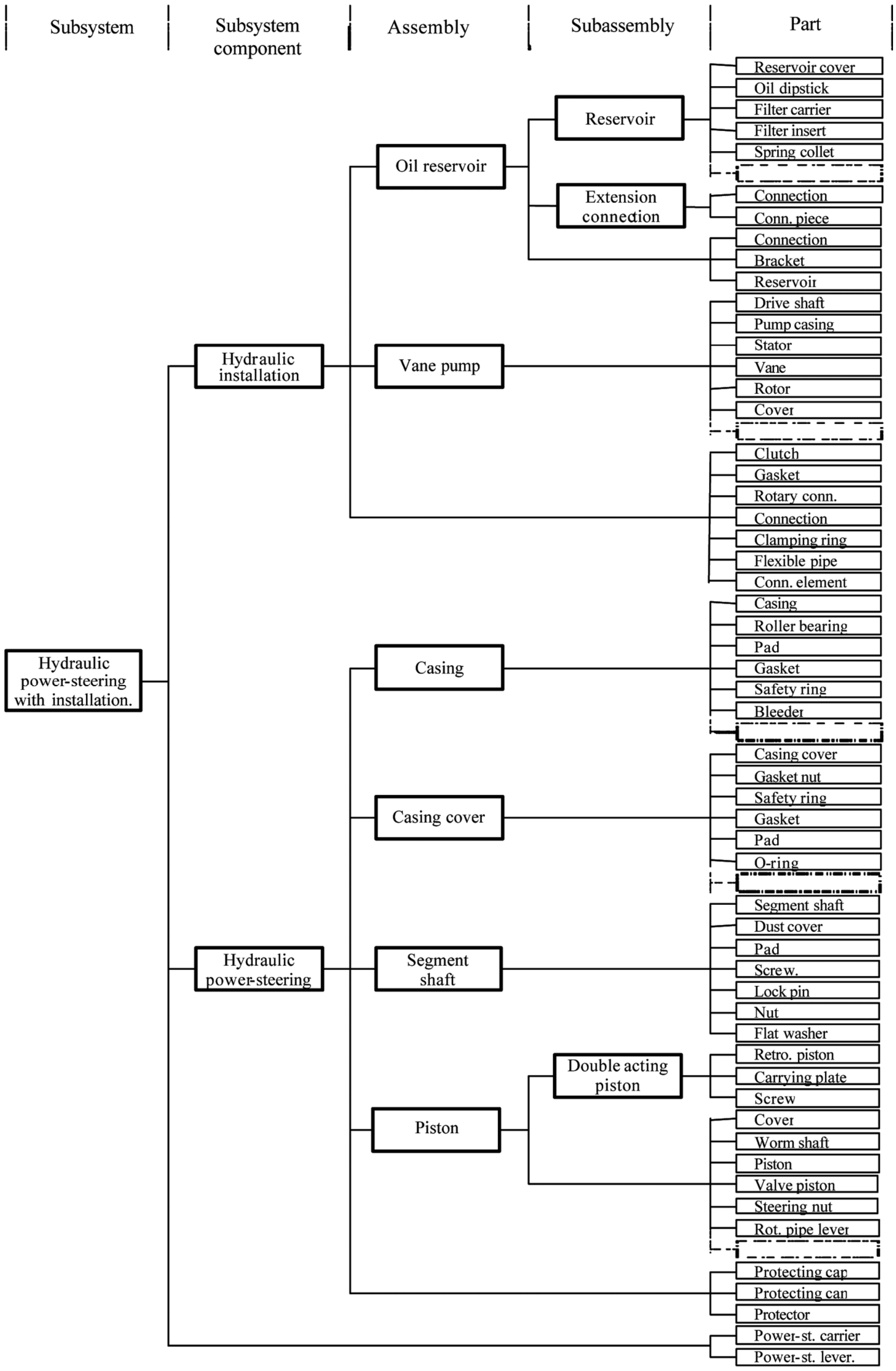
The functional principle according to the fault tree of HPS for light industrial vehicles is applied. The top event in the fault tree is the "Fault of hydraulic power steering (HPS) with installation", where it means a full or partial loss of working capacity of the considered system. The intermediate events are defined in ways in which failures of the power steering are observed, i.e. using the features of failure. It is necessary to emphasise that some of the faults of intermediary cases are also common to other elements of the steering system and other structural assemblies of a motor vehicle.

Based on consideration of the particular faults of HPS elements with installation, it could be confirmed that every causal case, which leads to the top event, can be grouped into one of seven semi-top intermediary cases (Figures 6):

- interruption of mechanical connection input-output
- clearance in HPS exceeding the allowed value
- complete loss of power effect
- inefficient operation of HPS
- occurrence of impact and vibration at the steering wheel

- deformations of the HPS elements
- noise of HPS in working conditions.

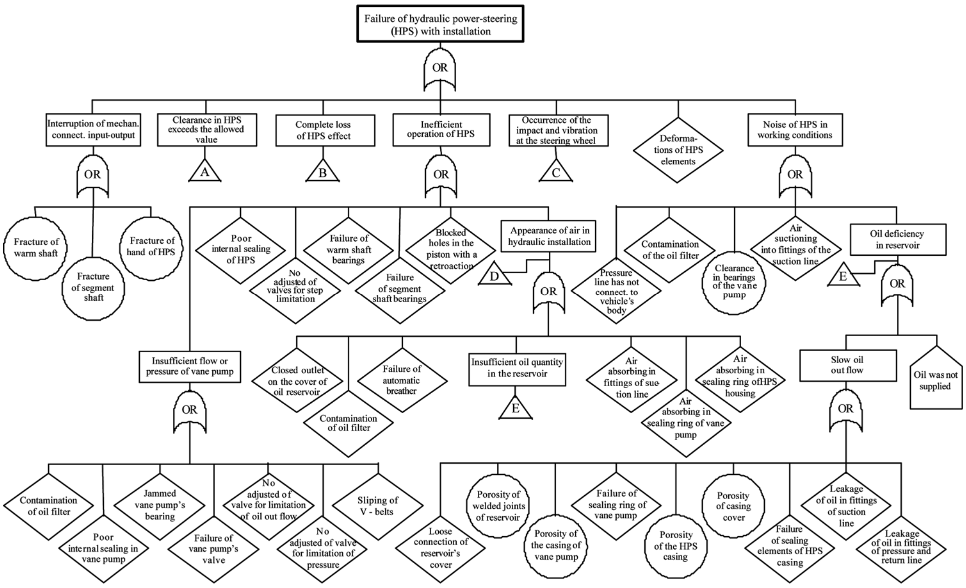
Figure 5 Scheme of distribution of hydraulic power steering with installation



The structure of the fault tree was augmented, in the form of the tree branches, by the deductive analysis of mentioned events by causes leading to them. In this way, in addition to identifying and tracking potential failure modes, a causal relation between the basic, intermediate and top events was established.

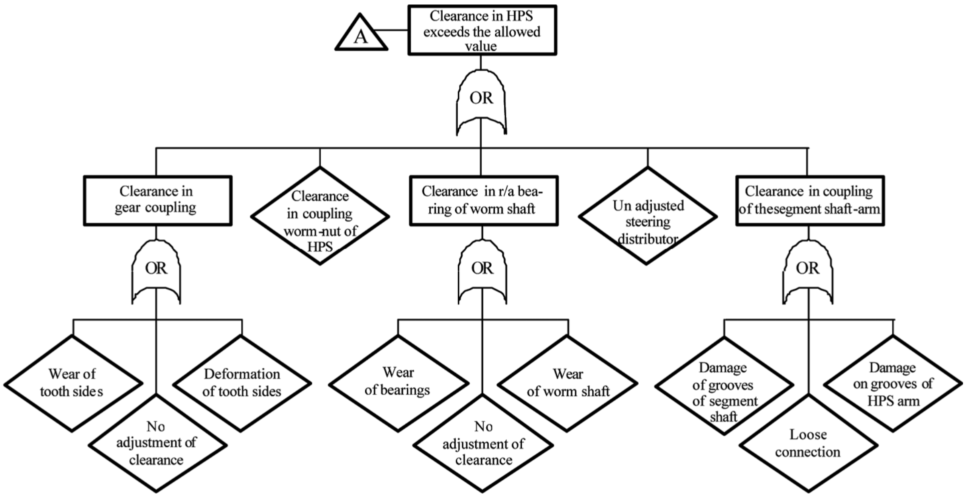
"Interruption of mechanical connection input-output" due to HPS element failures leads to full loss of working capability of the HPS and to immediate stoppage of the steering function. Since in this case it is a system with serial connection of elements, disruption of a functional link in the chain creates a complete failure of the steering system. Causes of this event appearance are most frequently primary failures (fractures) of elements (worm shaft, segment shaft or hand of HPS) due to fatigue, overload or impact loads.

Figure 6 Fault tree of hydraulic power steering with installation



The appearance of clearances in the steering system has a negative impact on the steering stability of a vehicle, and the preservation of proper turning kinematics of the wheels. The steering wheel, in straight-line driving, should have a minimum idle. Transport vehicles' idle should not be greater than 30º (Janicijevic et al., 1998). By exceeding the minimum allowable value of the clearance in the power steering and in other elements of the steering systems in straight-line driving, the vehicle cannot be perfectly controlled. A particular event, "Clearance in HPS exceeds the allowed value", is developed to show basic events in independent semi-tree shape, as shown in Figure 7. This event often occurs due to wear or plastic deformation of contact surfaces of the coupled elements, or due to loose connections of elements. In assemblies where the possibility for adjustment exists, the clearance might appear as a consequence of mismatch. Clearance in the power steering may occur in the gear's coupling, in the coupling worm – nut of the steering wheel, in the radial–axial thrust bearing of the worm shaft due to an unadjusted steering distributor or in the coupling of the segment shaft-power-steering lever.

Figure 7 Independent fault semi-tree for top event “Clearance in hydraulic power steering exceeds the allowed value”



Technical solutions for a gear segment with conical teeth and a screw at the end of the segment shaft enable adjustment of clearance in gear coupling of the piston and the segment shaft. Adjustment of clearance is performed in the middle position of the elements of gear transmission by unscrewing and screwing the adjustment screw, with simultaneous measurement of friction torque on the input shaft or torque required to rotate the segment shaft, when the power-steering lever is not mounted on it. For a certain type of power steering, friction torque must be within predetermined limits (Technical conditions for receiving and testing of power-steering, 1997).

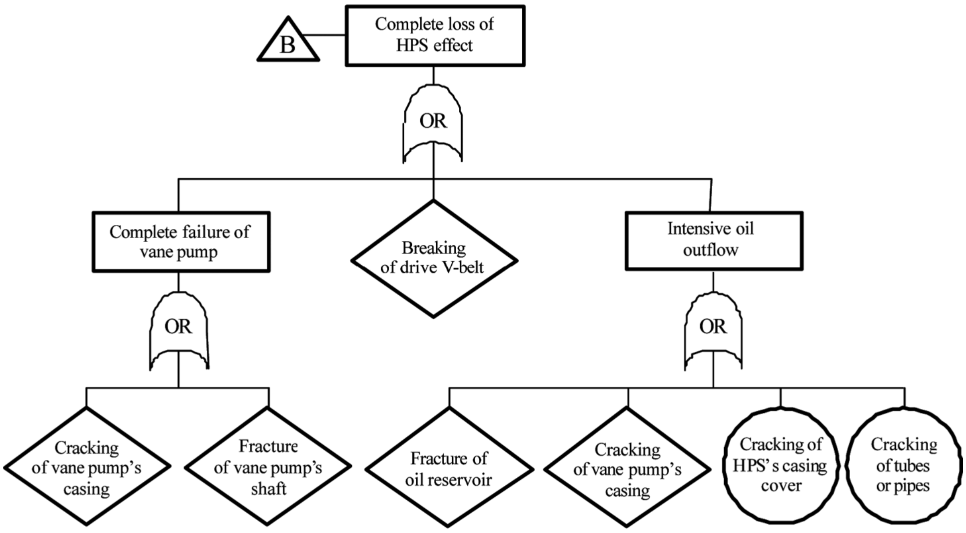
Clearance in coupling the worm–power steering nut can be adjusted. Therefore, if due to heavy load or inadequate maintenance, wear of elements occurs and clearance appears in coupling, the damaged parts have to be replaced.

Adjustment of clearance in the radial – axial ball bearing of the worm shaft is done by the winding ring in the casing cover, which also serves for axially fixing of bearing.

Wear of sliding surfaces of machine elements is a continuous process that lasts from the beginning of exploitation of the system. Wear intensity can be controlled by preventive maintenance (timely pouring and changes of oil, replacement of worn sealing elements, tightening screws, etc.). Nevertheless, the appearance of clearances in some elements over time is inevitable. Failure of elements due to the occurrence of clearance arises as soon as the clearance reaches a certain (threshold) value after which the functional characteristics, which depend on the clearance, get significantly worse. However, system failure may occur due to various combinations (superposition) of elements’ states, none of which has reached the threshold.

A semi-tree of faults for “Complete loss of HPS effect” is given in Figure 8. This event appears due to complete failure of the vane pump or breaking (fracture) of the drive V-belt, or due to intensive oil outflow when oil does not reach the chambers in the HPS casing. Complete failure of the vane pump appears due to fracture of the casing or cracking of the pump shaft. Intensive loss of oil appears due to fracture of the oil reservoir, cracking of the vane pump casing, cracking of the covers of the HPS casing or cracking of the tubes or pipes.

Figure 8 Independent semi-tree fault for top event “Complete loss of HPS effect”



Intermediate event “Inefficient operation of HPS” is manifested as augmented required torque on the wheel of HPS or as difficulties in steering. This relatively complex event is a consequence of: insufficient flow or pressure of the vane pump; poor internal sealing of the HPS chamber; improper adjustment of the valves for the hydraulic step limitation; increased friction of the sliding surfaces of the mechanism elements (failure of both worm and segment shafts); blocking of small holes on the piston backwards motion; or if the hydraulic installation contains air.

Insufficient flow or pressure in the vane pump is a consequence of high resistance in the suction line because of oil filter contamination, internal losses of poor sealing between blades, stator and distribution plates. Other causes are difficulties in pump shaft rotation because of jamming of bearings and failure of the vane pump valves: badly adjusted valves for flow limitation (adapted for less flow); badly adjusted valves for pressure limitation (to activate at significantly lower pressure). The sliding of V-belts used for driving the pump because the V-belts were not tightened sufficiently, or their excessive wear could be causes too.

Reduced efficiency of the vane pump is especially prominent at fast rotation of the steering wheel, when the pump is not able to provide the necessary amount of oil.

Damage to the internal sealing elements in HPS leads to internal losses, namely, to leakage of oil from the pressure chamber into the second one, or into the return line. Checking internal sealing is done by measuring the flow of oil on the test bench, with a working pressure of 100 bar. During this process, the total internal losses of oil for every type of power steering must not be greater than 2.5 l/min (Technical conditions for receiving and testing of power steering, 1997).

Lack of adjustment of one or both valves for hydraulic step limitation can lead to difficulties in steering (premature activation of the valve) or to overload of the vane pump, if in the limit positions valves are not activated. Furthermore, the presence of a foreign object in the valve seat, which prevents its complete closure, significantly reduces the power effect during steering.

Appearance of air in the hydraulic installation could be a result of closed outlet on the cover of the oil reservoir; contamination of the oil filter; failure of the automatic breather; insufficient oil quantity in the reservoir; or the presence of air in the suction line fittings or the sealing ring of the shaft of the vane pump or the sealing rings of the HPS casing; low pressure in the accessories could be a cause, too. Suction of air is especially prominent if a congestion of the suction line occurs that causes an exceeding of the allowed value of under pressure.

Residual air, which is not noticeable during driving, is automatically separated to the surface of the oil in the tank during operation. Because of this, the tank must not be filled to the brim with oil, and the vent on the lid of the tank must be clean. By using very foamy oils, the separation of air and breathing of the device is disabled. The automatic air vent in the casing of the power steering successfully performs its function if it is set at the highest level in the casing. Therefore, in the design phase, the mounting points for the air vent and the power steering on the vehicle must be harmonised. If during the operation, it is noticed that air has appeared in the steering mechanism, although all the threaded joints are tightly fastened, it is recommended that line connectors should be coated with lacquer (especially the suction line connectors) to prevent suction of air.

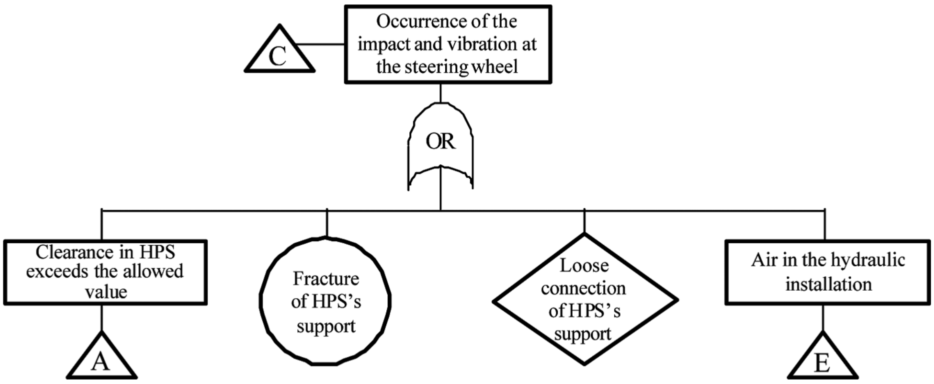
Purity of the operating fluid – oil – is of great importance for reliable and safe operation of the hydraulic power steering. Presence of metal particles, dust and other impurities in the oil is a basic cause of a great number of basic events at the fault tree of the hydraulic power steering, along with installation issues (contamination of oil filter, automatic air vent failure, congested hole at double acting piston, etc.), all of which gives a special importance to oil filtering. According to the producer's maintenance instructions, it is necessary to change the oil and oil filters after a certain distance in kilometres has been travelled, which depends on the type of hydraulic power steering. In the meantime, oil should be regularly checked and added. Because of the importance and participation of potential effects of the presence of foreign particles within the hydraulic system, a sequence of preventive measures is conducted in the phase of manufacturing and mounting. Pipe connection openings must be closed with plastic covers during storage and transport of constituent components (oil reservoir, vane pumps and power steering). Removal of covers is done immediately prior to the mounting of pipeline, thus preventing dirt and foreign objects from entering the hydraulic system. Besides that, a rubber cover is placed at the input of the worm shaft, while a dust cover, filled during mounting with anti-corrosive grease resistant to water and having relatively high dripping point, is placed over the segment shaft between the casing and the power-steering lever.

"Occurrence of the impact and vibration at the steering wheel" (Figure 9) appears as a consequence of clearance in HPS (the strongest influence is from clearance on the gear and screw coupling), fracture of the HPS support or failure due to loose connections between the HPS and the vehicle's body. Air presence in the installation could be a cause, too.

The event "deformations of HPS elements" contains all permanent deformation of the constitutive elements that appear from production errors or overload in service. Because of its low probability of occurrence in normal operation, this event has not been developed as a separate sub-tree.

"Noise of HPS in working conditions" appears due to contact of the pressure line of the piping with the vehicle's body or engine parts, contamination of the oil filter, clearance in bearings of the vane pump, air suction into the fittings of the suction line or insufficient quantity of oil in the reservoir. High viscosity oil, similar to contamination of filter, can lead to higher under pressure in the suction line, and this can cause noise during pump operation.

Figure 9 Independent semi-tree of top event “Appearance of the impact and vibration at the steering wheel”



The main source of noise during the operation of the power steering is the vane pump. Operation noise is a common feature of volume pumps, regardless of the type of hydraulic system in which they are applied. Alternating changes in volume of the working chamber of the pump and connection of the working chambers to the suction and pressure line, cause abrupt changes (pulsation) of the output pressure, accompanied with hydraulic shocks and appropriate sound effects. The oscillations of pressure in the pump are spread through the working fluid into the pressure line of the hydraulic installations and excite oscillatory processes in it and a corresponding vibration of the mechanical elements of the hydraulic installation, due to inertia and compressibility of fluid. In addition, if there is a match of forced and natural frequencies of oscillation of elements, it may lead to a large jump in the amplitude of oscillations, and bursting of pipes and connectors may occur. With the increase of oil pressure and the pump’s shaft speed, the level of pump noise increases. The level and spectrum of noise frequency can serve as indicators of the quality of construction and manufacturing of the pump.

Contact between the pressure line and the vehicle’s body or engine parts can also cause severe noise. The problem is easily solved by providing sufficient space between parts of the vehicle and the pressure line, by placing rubber mounts if necessary.

Hydraulic power steering noise testing is performed by turning the steering wheel quickly to one side or the other, and then slowly returning it to the middle position. In addition, there should be no noise in the steering distributor, only a slight hiss.

Oil insufficiency in the reservoir could appear due to slow oil outflow or if the oil is not controlled or added over a long period. Light outflow is the consequence of the reservoir’s cover not being tightened enough; porosity in the homogeneous weld joints of the reservoir, vane pump casing or hydraulic power steering; failure of the sealing rings of the HPS casing; or loose connections in the suction and return pressure line.

The first check of the external tightness of the hydraulic power steering components is done on the test stand at the manufacturer’s factory (Technical conditions for receiving and testing of power steering, 1997). Power steering testing is done immediately after completion of installation. In this study, power-steering components are subjected to higher pressures than anticipated working pressures. Thus, for example, the maximum working pressure of the investigated power steering is up to 100 bar, while a pressure of 130 bar is used for the sealing test. In a similar way, the test of the return line is performed. The flow pressure in the return line is 5 bar, while 6.7 bars are used during testing. In addition, for two minutes or so, external oil leaks may not appear. Control of oil leaks on the suction line is performed when the pump is not working.

Checking the external tightness of the hydraulic power steering in service, according to the manufacturer, is done at a certain mileage for road vehicles, or after a certain number of working hours for special vehicles, all-terrain vehicles and tractors. By careful examination of the lines of hydraulic installation, after a certain period of operation of the power steering, unsealed places can be easily detected.

The fault tree in Figure 6 shows the use of the symbols 'house' for the events. The event "Oil was not supplied" is not really a failure event. This is an event that is normally expected to happen. The reason that this event is included in the review is to take into account all the events that could lead to a top event.

The appearance of high operating temperatures of oil is not considered in the framework of the developed fault tree, because it was assumed that the elements of the hydraulic power steering with installation are mounted at a proper distance from heat sources in the motor vehicle and that the pipelines for oil have suitable diameters. If the previous conditions are incorporated in the design phase and in determining the mounting places for components, the maximum allowable operating temperature of oil in the hydraulic system would not be exceeded.

Despite the teamwork and a desire by the authors of this study to include as many elements of potential failure of the hydraulic power steering with installation, the developed fault tree should not be considered as complete. In this case, it may be supplemented by other events with lower probability. Grouping of the original events, as well as defining the intermediary events can also be done in a different way.

If one starts from the fact that a high degree of technological discipline in our production environment is difficult to achieve and even harder to maintain, there is a justifiable concern that significant failure modes are omitted. Therefore, in formation of the fault tree, details related to the deviation of production processes should not be overlooked, because they are built-in disadvantages.

Long-term systematic acquisition of data on existing hydraulic power boosters, control results of manufacturing process, test results, user complaints, etc., can serve as a basis for undeveloped events in the fault tree to be developed to their own basic events.

Such a definition of top events and the structure of the device caused the existence of only 'OR' logic gates in the fault tree of the hydraulic power steering. This means that during each of the primary or secondary basic events, opening the 'OR' gate leads to the top event. Based on this, it can be concluded that all minimum cut sets of the events of a fault tree contain one member and that the ranking of basic events in terms of structural importance cannot be done, because they all have equal importance.

In this case, of the fault tree of a hydraulic power steering, which it is a device under development, there is a lack of data on the intensity or the probability of basic events, and thus, it was impossible to make a quantitative fault tree analysis.

5 Conclusions

By using the FTA method, a detailed analysis of mechanical systems from the aspect of failures could be performed. The obtained data makes possible a complex recognising of causes and modes of failures and also of the mutual dependence between particular potential modes of element failures.

The fault tree presents a convenient means for illustration of the advantages of the proposed solution, in comparison to other solutions, i.e., it is material for argumentative discussion. If the designed system has errors, the fault tree could help to find weak spots, and it could show how these spots cause unwanted events.

The top event development in the tree "Fault of HPS with installation" system for steering light industrial vehicles to basic primary and secondary events, provided quality and quantity analyses of the fault tree of the considered object.

By adopting sufficiently general top events in the fault tree and by their development to the basic events, the majority of the potential modes of failure of the components can be recorded, which can be, inter alia, used as one of the best Failure Modes and Effects Analysis models for analyses of causes and consequences of faults.

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