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*Full Length Research Paper*

# Steer-by-switch system design for vehicles

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**In this paper, design of a steer-by-switch system as a new technology to steer vehicles devoid of a steering wheel was described. In this method, steering of the vehicle was achieved by two push button switches which were related to the front wheels via an electro-hydro-mechanical system. The objective of this design was to eliminate the prejudicial effects associated with the utilisation of steering wheels in machines. Furthermore, this system provided a flexible and comfortable steering for drivers of heavy duty machinery and off-road vehicles as well as the feasibility of driving for invalid persons who were feeble in one hand. Modeling of the system was achieved to compare its characteristics with two common types of steering systems. To enhance the reliability of the system, an auxiliary steering system served as a safeguard against the failure of the main steering system.**

**Key words:** Circuit, hydraulic system, push-button switch, steering effort, steering wheel, vehicle.

## INTRODUCTION

There are various types of steering systems based on the kind of devices and their applications. In most of the types, a steering wheel is counted as the most important component of the steering system. The use of a steering wheel in automobiles has grown into a habit, and a lack of a wheel is an abnormal condition for drivers. However, it holds several disadvantages from the viewpoint of ergonomics which encourages the idea of utilising a steering system devoid of a steering wheel. One of the most important problems of the existing steering systems is steering effort. When the driver wants to steer the front wheels, he is confronted with a resistance. This resistance is based on the weight of the vehicle, friction and inertia forces. Thus, the driver must exert sufficient torque to overcome these forces. The steering effort is considerable for large vehicles, particularly at low speed, that do not have hydraulic or electrical power steering (HPS or EPS), but have manually operated steering systems. As Kim and Song (2002) mentioned, the steering effort gradually causes annoyance and discomfort for the driver. Another problem is related to the hand-arm vibration. The drivers are continuously exposed to the steering wheel vibration which is transmitted to the drivers' hands. This vibration is created by various sources such as tire-wheel unbalance, road surface irregularities, engine unbalance during engine idling and imperfection of the suspension and steering mechanism. Gescheider et al. (2004) believed that the steering wheel hand-arm vibration is particularly important due to the sensitivity of the skin tactile receptors of the hand and due to the lack of intermediate structures such as shoes or clothing which can attenuate vibration. Kim et al. (1985) found out that vibration can be transmitted to the steering wheel at frequencies up to about 200 Hz with the greatest transmissibility around 20 to 30 Hz. Morioka and Griffin (2009) believed that discomfort, annoyance or interference with activities due

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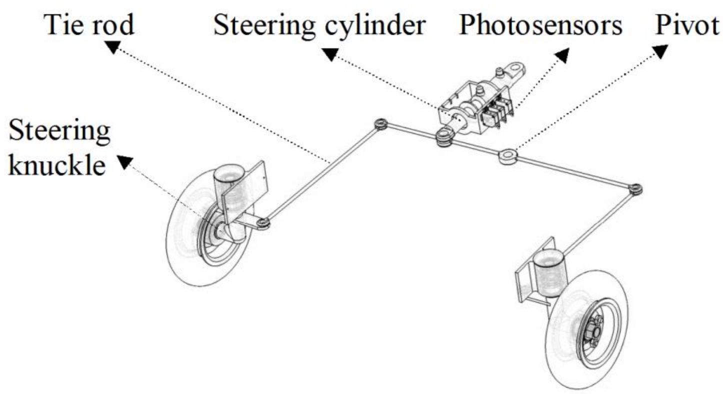


**Figure 1.** Connection between steering hydraulic cylinder and front wheels.

to vibration is expected if the vibration exceeds the threshold for the perception of vibration. Steering wheel vibration can produce a wide variety of different effects on the operators. Goglia et al. (2003) concluded that the vibration acceleration level transmitted from the steering wheel to the drivers' hands will produce finger blanching in 10% of exposed persons after less than 2 years.

The next problem is the grip force that the drivers normally apply to the steering wheel during driving to control machine movement. Many researchers have studied the steering wheel grip force characteristics of the drivers as a function of road, conditions, speed and gender and its effects on comfort, annoyance and hand-arm vibration transmission (Reynolds, 1977; Pyykko et al., 1976; Burstrom and Lundstrom, 1994; Haasnoot and Mansfield, 2007; Gurram et al., 1995). The other problem is impact of the steering wheel during a frontal crash. The steering wheel is the first location that the driver hits during an accident. The impact of a frontal crash will force the steering wheel to intrude into the driver's survival space. There are also some researches in the fields of design of steering systems (Aghkhani et al., 2009; Wang et al., 2011), driver hand position on the steering wheel (Waard et al., 2011) and torque fluctuation of steering system (Xue et al., 2011). In steer-by-switch system, two push button switches substitute for the steering wheel, which are related to the front wheels via an electro-hydro-mechanical system. This system is appropriate for heavy duty machinery and off-road devices. The aim of this research is to design a steering system devoid of a steering wheel to eliminate the prejudicial effects associated with the utilisation of steering wheels in machines and to provide a flexible and comfortable steering for drivers.

## DESCRIPTION OF THE MECHANISM

In the steer-by-switch method, the steering action is performed by push-button switches which require the least effort to be actuated. The electro-hydro-mechanical system is composed of a hydraulic solenoid valve, a hydraulic cylinder, two push button switches, two contactors and three photo sensors. The hydraulic cylinder is connected to front wheels via tie rods and steering knuckles (Figure 1). A hydraulic circuit consists of a motor-pump, an oil tank and several hydraulic valves are necessary to supply the oil to the hydraulic cylinder. In this system, by pressing a button switch, the front wheels turn to left or right. By releasing the button switch, the wheels will automatically return to the straight condition.

## DESCRIPTION OF THE COMPONENTS

The main components of a steer-by-switch system are photo sensor, contactor, hydraulic solenoid valve and push-button switch. The photo sensor opens the circuit when a target is located in front of it. As Figure 2 shows, three photo sensors are placed in a frame which is attached to the steering hydraulic cylinder. A metal ring attached to the piston rod of the cylinder moves in front of the photo sensors as a target. The middle photo sensor is used for the straight movement and two other photo sensors are used to limit the turning of the front wheels. The contactor is a magnetic switch used for switching a power circuit. It is composed of a case, an electromagnet, a spring and several moving and fixed contacts. When current passes through the electromagnet, a magnetic field is produced that attracts the moving core. The force developed by the electromagnet holds the moving and fixed contacts together. The current enters the electromagnet through the contact A1 → A2 of the contactor. In the hydraulic solenoid valve, the port opening can be achieved by a current flow through the coils. A magnetic field provides electromotive force to

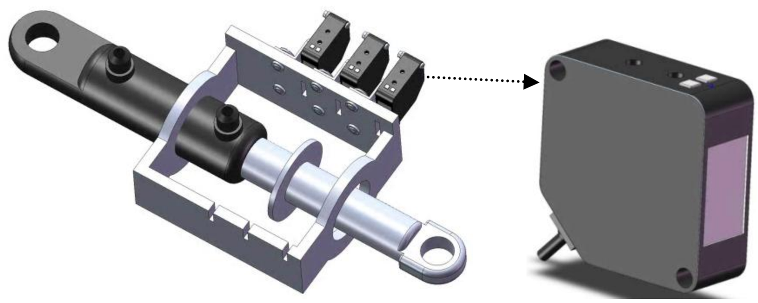

**Figure 2.** Steering hydraulic cylinder with photosensors and target.

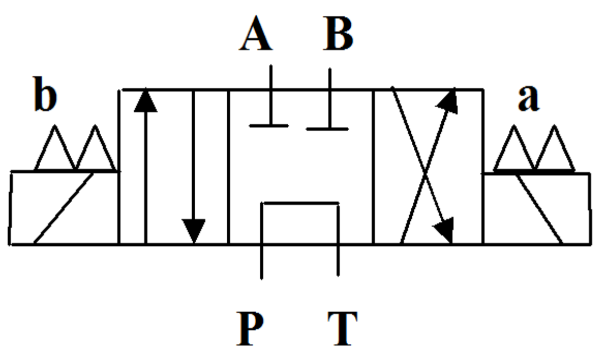


**Figure 3.** Solenoid valve symbol.

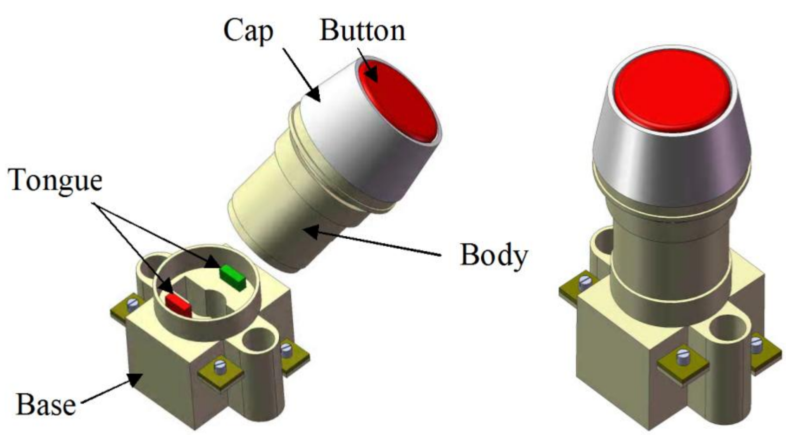


**Figure 4.** Change over switch.

move the specially shaped valve spool. This motion is opposed by a centring spring. The ports are represented by pump P, the return tank T, the actuator inlet chamber A and the actuator outlet chamber B (Figure 3). The push-button switch operates as a stop or start switch. The start switch allows current to flow only when the button is pressed, whereas the stop switch is normally closed and is opened (off) when the button is pressed. Two stop and start switches may be attached to make a double-stop-start switch (change-over switch).

Pressing the button will actuate both switches simultaneously (Figure 4). Single stop and start switches may be attached to make multiple switches that are actuated by a button.

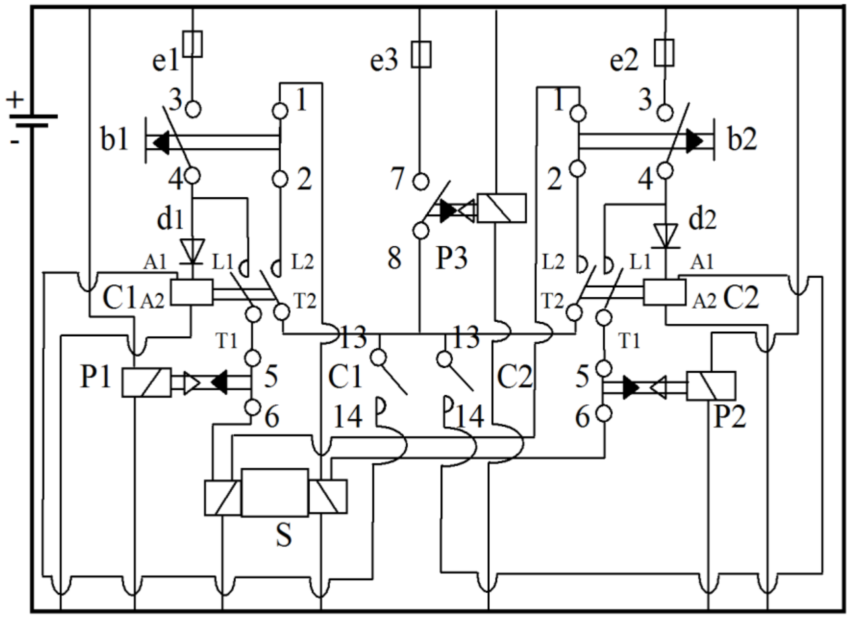


**Figure 5.** Scheme of the DC electrical current circuit for the steer-by-switch method. b: double start-stop switch, S: solenoid valve, P: photo sensor, C: contactor, d: diode and e: fuse.

## STEERING PROCESS

On all steering systems, the steering process consists of three steps including turning to the left or right, stopping steering and returning to the straight condition. All steps are achieved by a steering wheel. However, in the steer-by-switch method, these steps are performed by electrical switches. Figure 5 depicts the DC electrical circuit of this system. This circuit is composed of three sections. The left section is used for left steering, the right section for right steering and the middle section for returning the front wheels to the straight condition. For left steering, the double stop-start switch b1 is pressed. Contact 1 → 2 is opened and 3 → 4 is closed. The current flows through 3 → 4 and is divided into two discrete directions. One direction flows through A1 → A2 of contactor C1 and induces the electromagnet to close the power contacts of L1 → T1, L2 → T2 and 13 → 14 of the contactor. Therefore, another direction flows through L1 → T1 and enters the solenoid valve to open one of its ports, for instance, A. Oil flows to steering cylinder through this port. The steering cylinder pushes the tie rod, and the tie rod turns the steering knuckle and front wheels to the left. On the other hand, when the hydraulic cylinder begins to move, the target passes in front of the photo sensor P3 and causes the contact 7 → 8 to be closed. The current flows through this contact and contacts 13 → 14 and L2 → T2 of contactor C1 but is stopped at contact 1 → 2 of b1 because it is still open. When the operator releases switch b1, contact 3 → 4 is opened and 1 → 2 is closed. Accordingly, the current to the solenoid valve is interrupted, and left steering is stopped. The contacts L2 → T2 and L1 → T1 are still closed because contact 13 → 14 sends the current from P3 to electromagnet of C1. At this time, the current from P3 flows through 2 → 1 and enters the opposite side of the solenoid valve. Port A is closed, and port B is opened. Oil flows to the opposite side of hydraulic cylinder and pulls the tie rod. The front wheels turn to the opposite direction. This action continues until the target is again in front of photo sensor P3.

Contact 7 → 8 is opened, and current through P3 is interrupted. Therefore, contacts L1 → T1, L2 → T2 and 13 → 14 are opened and steering is stopped. This situation is the straight condition of the front wheels. As a result, two steps of the steering process are achieved by pressing and releasing switch b1. Pressing the switch will turn the front wheels to the left or right, and releasing it returns the wheels automatically to the straight condition. Diodes d1 and d2 prevent the return of current to the solenoid valve through L1 → T1 when the start switches are opened. To limit the angle of turning in the front wheels, two other photo sensors P1 and P2 are used. However, the third step of steering process could be achieved in the steer-by-switch method. This step is to stop the turning of front wheels during steering. To perform this action, a modification should be applied to the structure of double-switches. It means that two stop

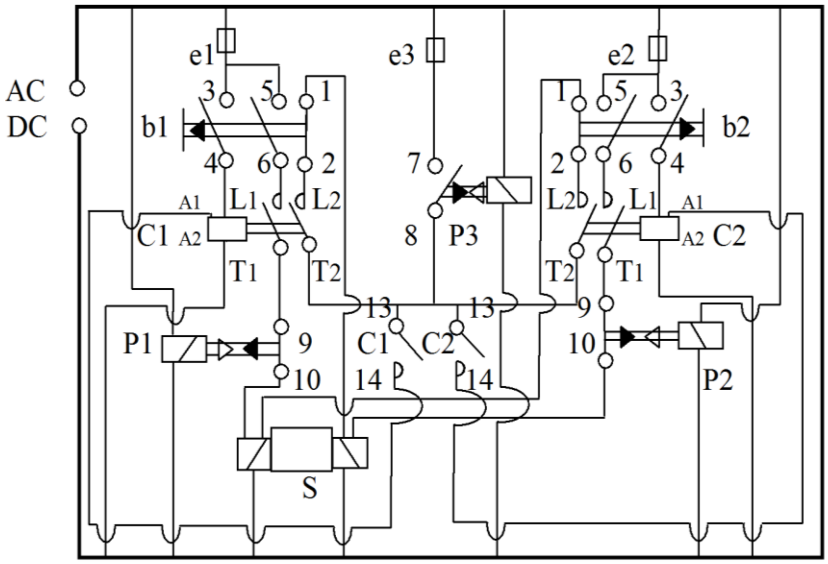


**Figure 6.** Scheme of the electrical current circuit for the steer-by-switch method. b: triplet switch, S: solenoid valve, P: photo sensor, C: contactor and e: fuse.

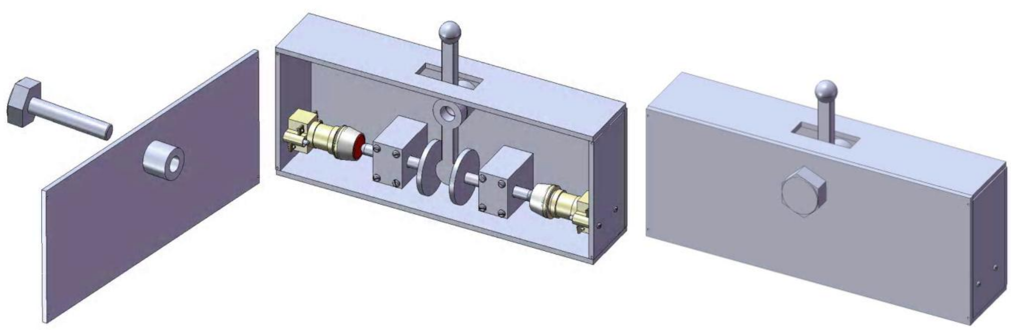

**Figure 7.** Integrated switch box.

and start switches should not act simultaneously. At the beginning of steering, the stop switch must be actuated at first because the current should not flow through 1 → 2. Switch b1 is modified by selecting the tongue of the start switch to be shorter than that of the stop switch so that by pressing the switch, the stop switch is actuated, 1 → 2 is opened and, after a while, the start switch is actuated and 3 → 4 is connected. By releasing the switch, the start switch is opened first, and after a while the stop switch is actuated and closes contact 1 → 2. Therefore, there is an interval between the operations of the two switches. In this interval, the steering action is stopped. This step is the third step of the steering process. Similarly for right steering, double switch b2 is pressed.

Another configuration of this circuit, which is used for both DC and AC current, may be obtained by replacing the double switch with a triplet switch (two start-one stop switches). In this case, the diodes are deleted from the circuit (Figure 6).

## INTEGRATED SWITCHES

Two double switches b1 and b2 may be integrated into a box to be actuated with a single hand lever. This configuration provides the more comfortable mechanism for steering (Figure 7). By moving the handle to left or right, switches b1 and b2 are pressed, and three steps of steering are achieved.

## PROTECTION AGAINST FAILURE OF STEERING

With this kind of steering, a safeguard is needed in the

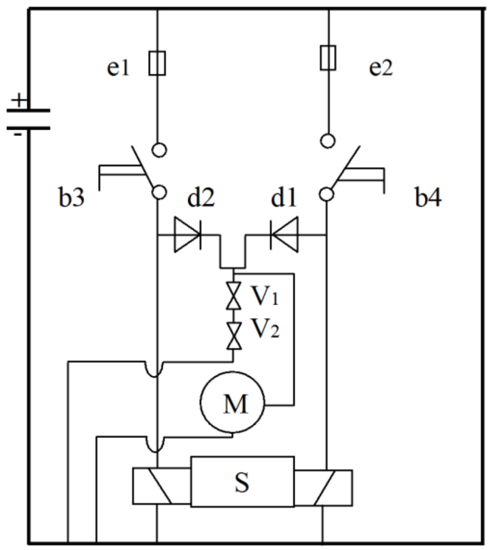


**Figure 8.** DC electrical circuit for auxiliary system. b: start switch, d: diode, M: electro motor, e: fuse, S: solenoid valve and V: shut-off solenoid.

case that the pressure oil supply or electrical circuit fails. Otherwise, the machine could not be steered because there is no mechanical link between the switches and front wheels. Therefore, an auxiliary system consisting of an independent hydraulic and electrical circuit was considered to substitute with the main steering system when it is confronted with a problem. The auxiliary system has no relationship with the main steering system. As Figure 8 illustrates, the electrical circuit is composed of two start switches, a solenoid valve and two shut-off solenoid valves. The start switches can be mounted on the switch box. When one of the start switches is pressed, the current flows to the solenoid valve and opens its port. The current also flows to the electromotor-pump and shut-off valves and actuates them. The shut-off valves close the oil ducts of the main steering system to the steering cylinder, and simultaneously, the oil flows from a secondary reservoir, passes through the solenoid valve and is then directed to steering cylinder (Figure 9). In this case, steering of the vehicle is fully controlled by the operator. Another switch is used for steering on the opposite side. This is a temporary situation until the main system is fixed. For fast response of the steering cylinder, the oil should be trapped in the circuit by a check valve in the inlet of the pump.

Another way is to mount the oil reservoir at the top of the pump and solenoid valve to prevent the leakage of oil into the reservoir when the system is not active. This system also allows the steering to be performed in the stop condition when the engine is off.

## MANUFACTURING OF THE STEERING SYSTEM

The integrity of the steering system was verified by manufacturing and installing it on a scale model of a wire remote control crane with a complete hydraulic system (Figure 10). The operation of steering could be controlled by two double-switches in the control box of the crane. A photo sensor was mounted on a small hydraulic cylinder to automatically straighten the front wheels after steering.

## MODELING OF THE STEERING SYSTEM

The dynamic model of the system is presented to compare the characteristics such as steering effort and steering sensitivity with the mechanical and hydraulic steering systems.

### Dynamic model of the mechanical steering system

Figure 11 denotes a schematic of the mechanical steering system. The required torque to turn the front wheels in a steering process is obtained by the following equation:

$$T_W = Wu\sqrt{\frac{B^2}{8} + E^2} \qquad (1)$$

Where Tw is the kingpin torque (N - M), W is the weight of vehicle on steered axle (N), u is the coefficient of friction between the tire and road which is assumed 0.7 for more applications, E is kingpin offset (m). Consequently, the required force to turn the front wheels can be written as:

$$F_W = \frac{T_W}{r_K} = Wu\sqrt{\frac{B^2}{8} + E^2} \qquad (2)$$

Where rk is the kingpin arm. This force is transmitted to the steering wheel through the rack and pinion. Figure 12 shows the free-body diagram of rack in a mechanical steering system.

It is exposed to four external forces. Ff is the friction force due to the losses in the system, Fw is applied from the front wheels, $m_k\bar{a}$ is produced due to the acceleration of the mass of tie rod, kingpin arms and the front wheels, Fp is the contact force of the pinion acting on the rack to overcome the three other forces and is equal and opposite to the contact force of the rack acting on the pinion. Therefore, the force and torque of the pinion can be written by the following equations:

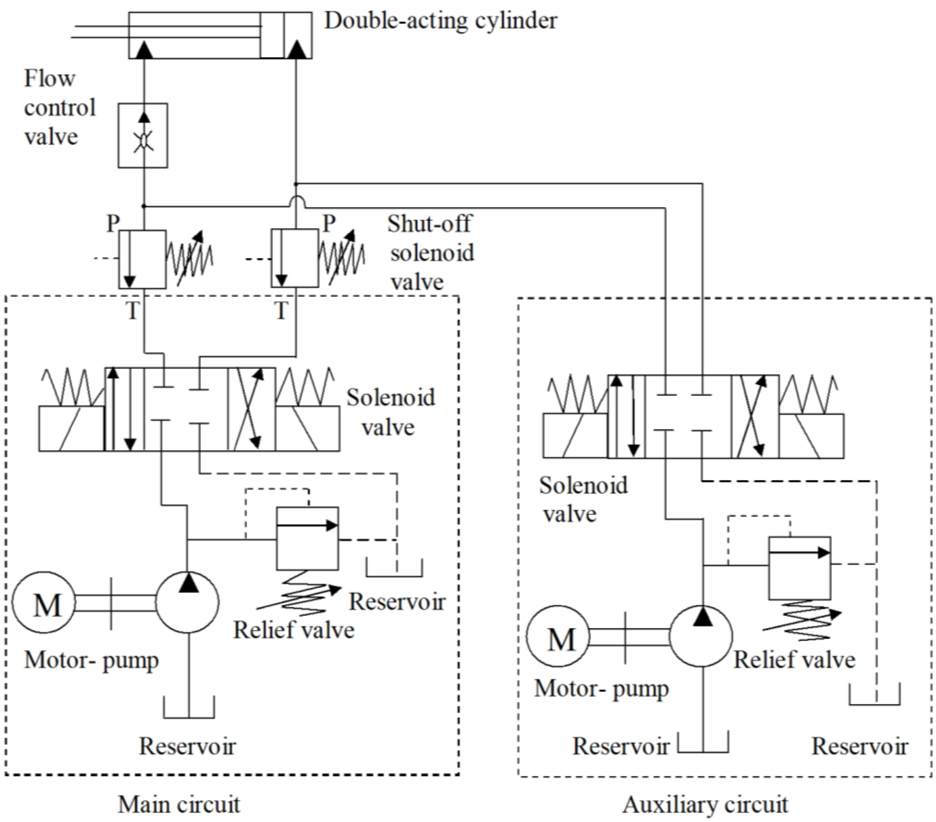


**Figure 9.** Schematic of the hydraulic system for the steer-by-switch method.

**Figure 10.** Steer-by-switch system mounted on a wire remote control crane.

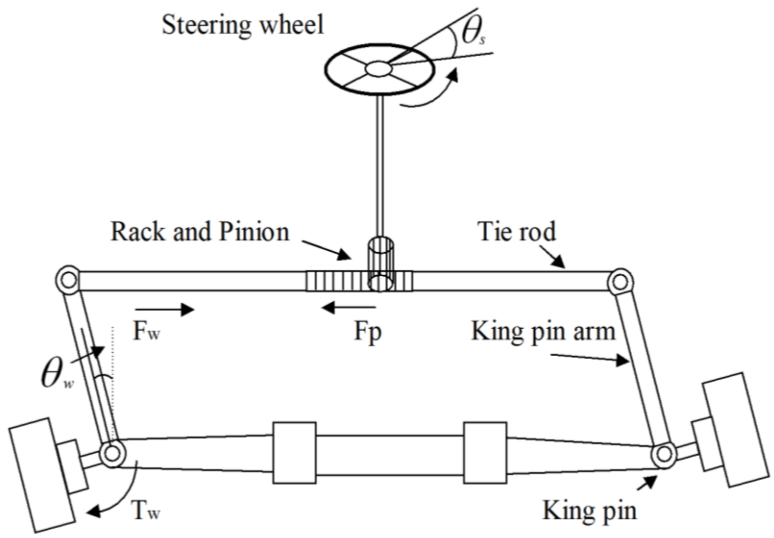


**Figure 11.** Schematic of the mechanical steering system.

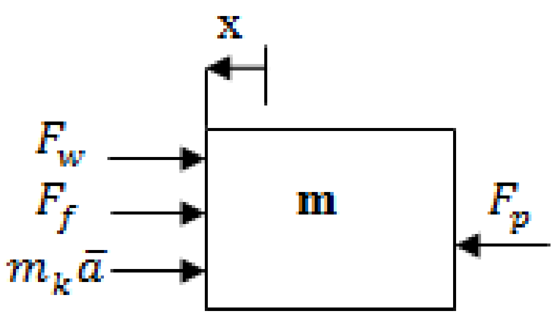


**Figure 12.** Free -body diagram of the rack.

$$F_P = F_f + F_W + m_k \bar{a} \tag{3}$$

$$T_P = F_P \times r_P = (F_f + F_W + m_k \bar{a}) \times r_P \tag{4}$$

Since the steering wheel, steering wheel shaft and pinion are as a rigid body, therefore:

$$T_P = T_S$$

and the equation of motion can be obtained for the steering wheel in the form:

$$F_d \times r_S - T_P = \bar{I}_S \ddot{\theta}_S \tag{5}$$

Where Fd is the force applied to the steering wheel by driver, rs is the radius of the steering wheel, $\bar{I}_S$ is the mass moment of inertia of the steering wheel and steering shaft, $\ddot{\theta}_S$ is the angular acceleration of the steering wheel, Ts is the torque of the steering wheel.

Substituting the values of Tp and Fw in the Equation 5, the following equation is obtained:

$$F_d = \frac{(F_f + F_W + m_k \bar{a}) \times r_P + \bar{I}_S \ddot{\theta}_S}{rs} \tag{6}$$

Consequently, the steering effort can be obtained as:

$$T_d = (F_f + F_W + m_k \bar{a}) \times r_P + \bar{I}_S \ddot{\theta}_S \tag{7}$$

This is the required torque for the driver to steer the front wheels. The required work and power of the driver can be obtained as:

$$U = F_d r_S \theta_S = [(F_f + F_W + m_k \bar{a}) \times r_P + \bar{I}_S \ddot{\theta}_S]\theta_S \tag{8}$$

$$P = \dot{T} = \frac{d}{dt}\left(\frac{1}{2}\bar{I}_S \dot{\theta}^2\right) = \bar{I}_S \ddot{\theta}_S \dot{\theta}_S = \bar{M}\,\dot{\theta}_S \tag{9}$$

## Dynamic model of the power steering system

In a power steering system, a hydraulic cylinder attached

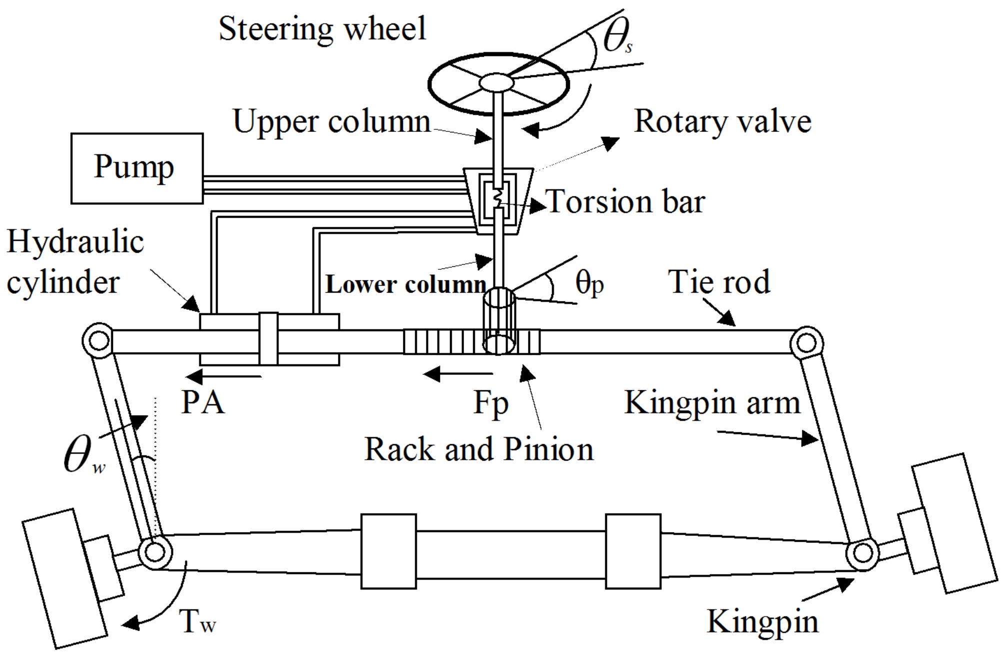


**Figure 13.** Schematic of the power steering system.

to the rack aids the mechanical system to reduce the steering effort (Figure 13). A rotary or torsion valve located at the beneath of the steering wheel guides the oil coming from the pump to the hydraulic cylinder when the steering wheel is rotated by the driver. The steering column is divided into the upper and lower column. The torque of the driver is transmitted to the torsion bar that twists with an angle of θ. Therefore, an opposite torque is produced proportional to the twist of the bar ($\Delta\theta = \theta 1 - \theta 2$). The twist of the torsion bar varies the position of the orifices at the rotary valve. Thus, the difference of the pressure is increased at both sides of the hydraulic cylinder and moves its piston and the rack. The torsion bar also transmits the torque of the driver to the pinion and the rack and helps the hydraulic cylinder to overcome the resistant forces. The model for the torsion valve is a torsion spring with a spring constant Kv. The steering effort in this system can be obtained from the following equations of motion:

$$T_d = K_V.\Delta\theta + \bar{I}_S \ddot{\theta}_S \tag{10}$$

$$F_d = \frac{K_V.\Delta\theta + \bar{I}_S \ddot{\theta}_S}{r_S} \tag{11}$$

Where Kv is the elasticity of the torsion bar. The steering effort can be also written as:

$$\frac{T_d}{r_S} + P.A = F_f + F_W + m_K \bar{a}$$

$$T_d = (F_f + F_W + m_K \bar{a} - P.A) r_S \tag{12}$$

**Dynamic model of the steer-by-switch system**

Dynamic model of the system is accomplished with the assumption that the consumed power of the electrical system is waived, because it does not have any effect on the steering effort. In this system, there are not any steering wheel, steering column, rack and pinion (Figure 14). The equilibrium equation omitting the friction forces can be written as:

$$PA - F_W - m_K \bar{a} = 0 \tag{13}$$

In this case, the required force for steering is provided by a hydraulic cylinder which is actuated by driver via pressing a lever. The driver's effort is consumed for pressing the spring of the push-button switch. The required force to rotate the steering lever is written as:

$$F_d = K r_l \theta_l \tag{14}$$

The equation of motion can be written as:

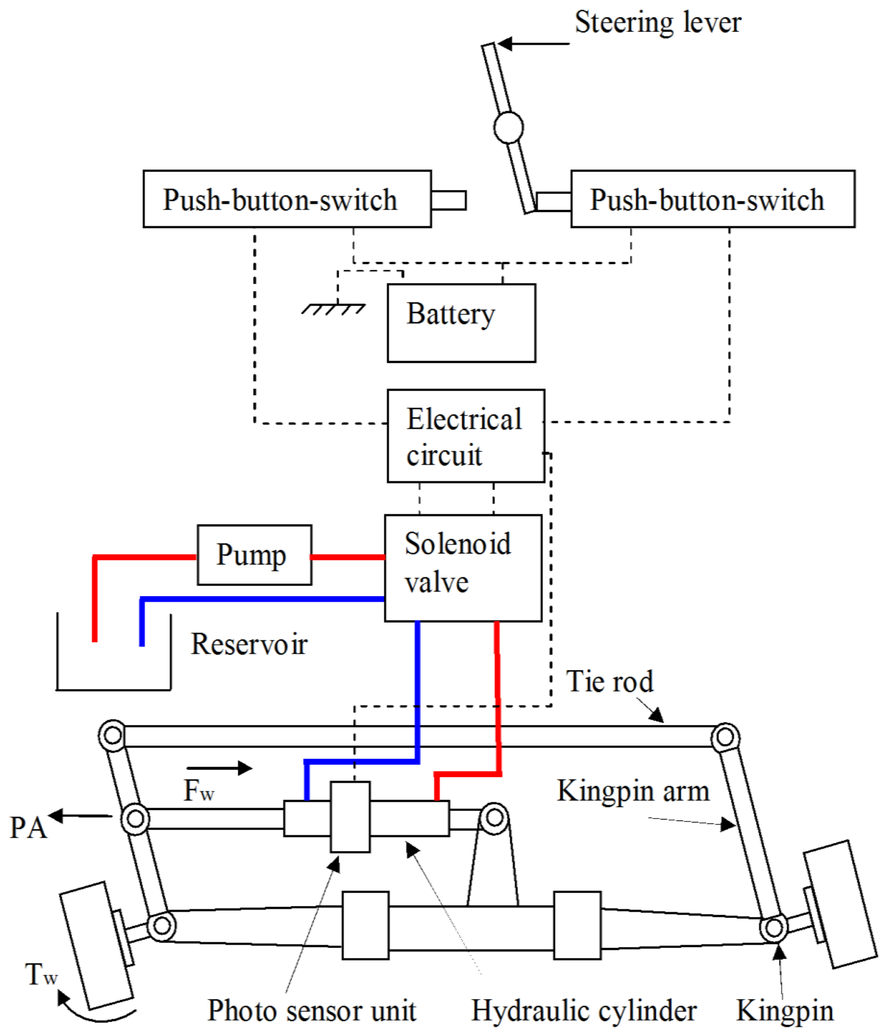


**Figure 14.** Schematic of the steer-by-switch system.

$$F_d \times r_l - K r_l^2 \theta_l = \bar{I}_l \ddot{\theta}_l \quad (15)$$

The steering effort can be obtained as follows:

$$T_d = \bar{I}_l \ddot{\theta}_l + K r_l^2 \theta_l \quad (16)$$

Where:

Fd is the force of the diver, K is the spring constant, rl is the radius of the lever, θL is the angle of rotation of the lever, $\bar{I}_l$ is the mass moment of inertia of the lever about the mass center, $\ddot{\theta}_l$ is the angular acceleration of the lever.

The required work for turning the front wheels to left or right is expressed by:

$$U = K r_l \theta_l^2 + \bar{I}_l \ddot{\theta}_l \theta_l \quad (17)$$

The required power for steering can be written as:

$$P = \dot{T} = \bar{M} \dot{\theta}_l$$

$$P = F_d r_l \dot{\theta}_l = K r_l \dot{\theta}_l \theta_l + \bar{I}_l \ddot{\theta}_l \dot{\theta}_l \quad (18)$$

## NUMERICAL ANALYSES

To gain an approximate value for the steering effort and the required power, a Massey-Ferguson tractor model-

135 with the mechanical steering system and the following specifications was selected:

$$B=0.15m,\ E=0.02m,\ r_K=0.155m,\ u=0.7,\ m_K=40kg,\ u_K=0.6,\ r_P=0.015m,$$
$$r_S=0.215m,\ m_S=2kg,\ m_C=1.47kg,\ r_C=0.013m,\ \theta_W=60^\circ$$

Assuming that the weight on the front axle is W = 9813.3 N and substituting the aforementioned quantities into Equations 1 and 2:

$$T_w=388.37N-M,\ \ F_w=2505.6N$$

$$F_f=u_k m_k g=0.6\times40\times9.81=235.44\quad N$$

A turn to left or right with the angle of 60° must be accomplished in one second, therefore:

$$\dot{\theta}_W=\frac{\theta_W}{t_W}=1.04\quad rad/s$$

$$\bar{a}_K=\bar{V}_K=rK\dot{\theta}_W=0.155\times1.04=0.16\quad m/s$$

$$m_K\bar{a}=40\times0.16=6.4\quad N$$

$$\theta_S=\theta_W\times\frac{r_K}{r_P}=\frac{1.04\times0.155}{0.015}=10.74\quad rad=616^\circ$$

For t = 1 $\rightarrow\ddot{\theta}_S=\dot{\theta}_S=\theta_S=10.74\ \frac{rad}{S^2}$

The mass moment of inertia for the steering wheel and the steering shaft which construct a rigid body can be written as follows:

$$\bar{I}_S=m_S r_S^2+\frac{1}{2}m_C r_C^2=2\times0.215^2+\frac{1}{2}\times1.47\times0.013^2=0.092\qquad kg.m^2$$

Substituting the aforementioned magnitudes into Equation 6; we obtain Fd = 163.33 N. The steering effort and the required power for steering can be obtained as:

$$T_d=\bar{M}=F_P\times r_P=(F_f+F_W+m_K\bar{a})\times r_P=(235.44+2505.6+6.4)\times0.015=41.2\qquad N-M$$

$$P=\bar{M}\dot{\theta}_S=41.2\times10.74=442.5\qquad Watt$$

The similar calculations are accomplished for the steer-by-switch system. In this case, the maximum displacement of the lever is 10 mm. For a lever with rL = 0.1 m and a time of t = 1s,

$$\ddot{\theta}_l=\dot{\theta}_l=\theta_l=0.1\ \frac{rad}{S^2}$$

The mass moment of inertia for the lever with the diameter D = 0.01 m, the mass m = 0.12 kg and k = 1000 N/m is written in the form:

$$\bar{I}_l=\frac{1}{4}m_r^2+\frac{1}{12}m_L^2\rightarrow\bar{I}_l=0.0004\qquad kg.m^2$$

By substituting the aforementioned values into Equation 12:

$$T_d=0.0004\times0.1+1000\times0.1^2\times0.1=1\qquad N-M$$

$$P=T_d\times\dot{\theta}_l=1\times0.1=0.1\qquad Watt$$

Proca and Keyhani (1998) presented a dynamic model for the power steering system and estimated a value for Kv equal to 1.843 N-M/rad. The range of the torsion bar angle is (-0.06 ≤ Δθ ≥ + 0.06). Assuming that the specifications of the steering wheel resemble to the mechanical system and using Equation 10:

$$T_d=1.843\times0.06+0.092\times10.74=1.1\qquad N-M$$

$$P=T_d\times\dot{\theta}_S=1.1\times10.74=11.81\qquad Watt$$

## RESULTS AND DISCUSSION

The steer-by-switch system could be compared with the existing steering systems from several points of view. The most important subjects related to the ergonomic problems and health of the driver was the steering effort and the consumed power of the driver to perform each steering process. The next subject was the relationship between the force Fw exerted from the front wheels and the steering effort. The other subject was the relationship between the angular displacement and velocity of the front wheels and the steering wheel. Numerical analyses represented that the consumed power of the driver for steering in steer-by-switch system was negligible as compared with the mechanical and hydraulic steering systems and could not cause the fatigue and annoyance

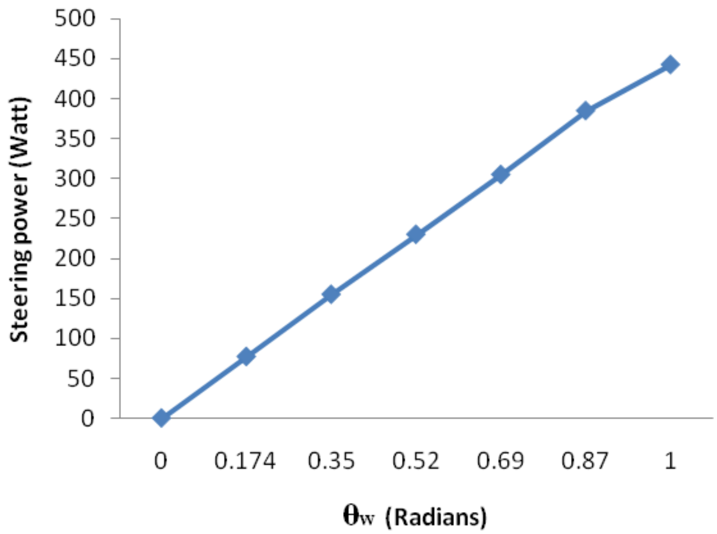


**Figure 15.** The required power for steering in a mechanical steering system.

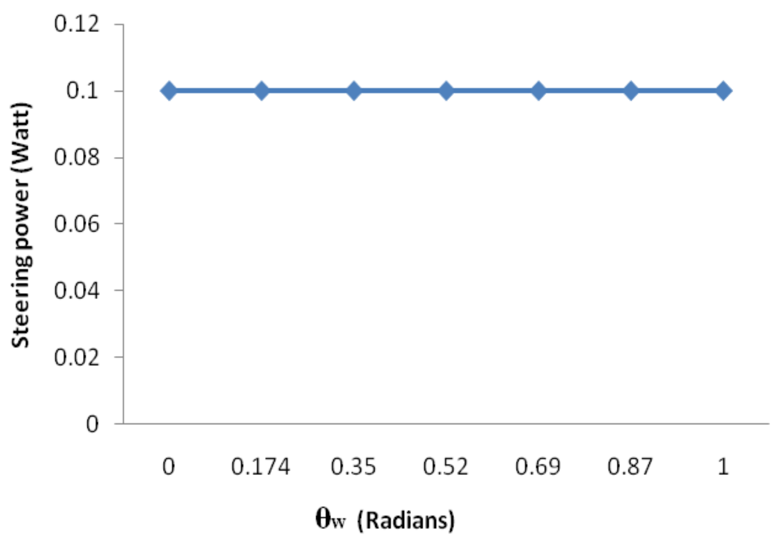


**Figure 16.** The required power for steering in the steer-by-switch system.

of the driver. Figures 15 to 17 depict the power of steering in a turn to the left or right in various steering systems. In Figure 18, the power of steering in the steer-by-switch system was compared with two other systems. In a mechanical steering system, the high required power for steering causes the fatigue, annoyance and damage of the driver in a long time. Another subject was related to the relationship between the increment of the force Fw exerted to the pinion from the front wheels and the steering effort. The amount of Fw was based on the weight of vehicle and specifications of the front wheels. Other factors such as vehicle speed might affect on the amount of this force. In a mechanical steering system, the steering effort was based on the value of Fw. Figure 19 denotes the relationship between the steering force and the force Fw in the mechanical and steer-by-switch systems. In the power steering system, the increment in the amount of Fw would result in the increment of $\Delta\theta$ and consequently, the pressure of the hydraulic system. Thus, the hydraulic cylinder applied more pressure for steering to prevail over Fw. However, the steering effort also varied with the change in $\Delta\theta$ , although its effect on the driver might not be perceptible. In any case, a definite relation could not be presented between Fw and the

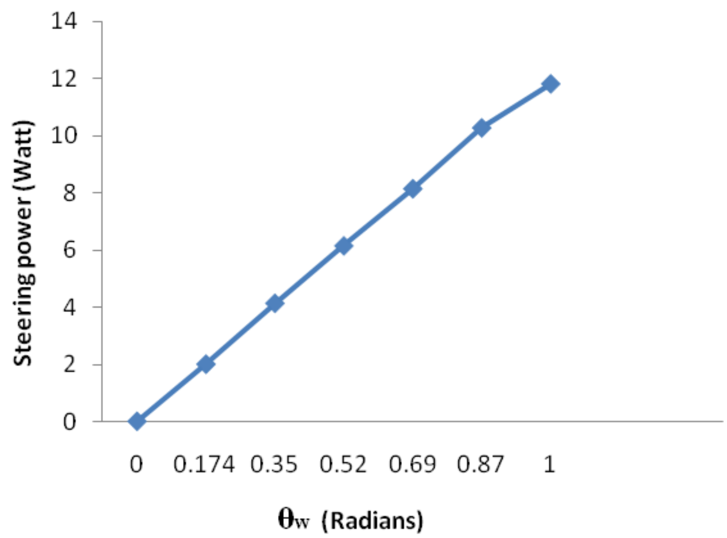


**Figure 17.** The required power for steering in a power steering system.

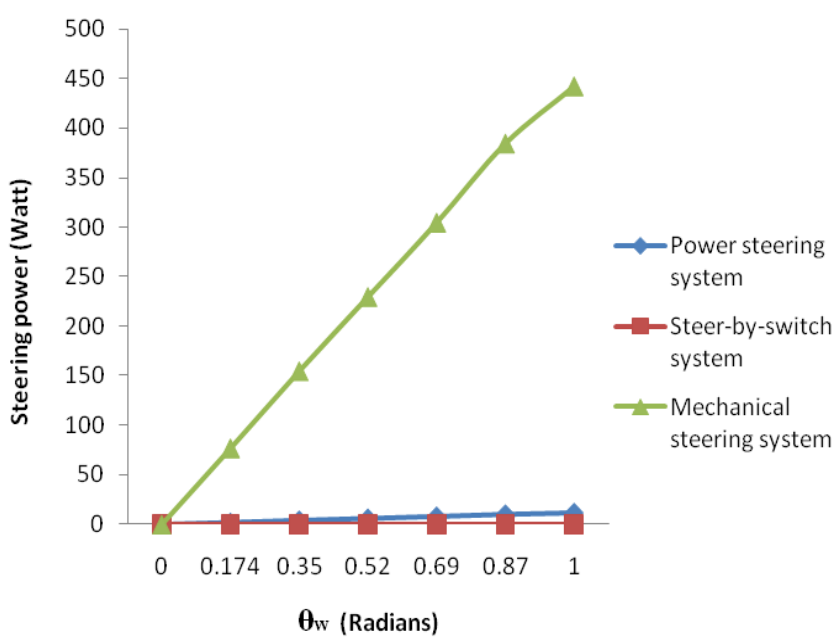


**Figure 18.** The required power for steering in three steering systems.

steering effort in this system, because it might vary in different vehicles.

As Figure 19 represents, there was not any relationship between Fw and the steering effort in the steer-by-switch system due to lack of a hydraulic or mechanical connection between the steering lever and the front wheels. This specialty could be useful in heavy-duty machinery. The next subject was related to the relationship between the angular displacement of the front wheels and the steering wheel in the mechanical steering system. This relation was based on the ratio of rp/rs. Therefore, for a ratio of rp/rs = 1/6 and a turn to left or right with the angle 60°, the steering wheel had to rotate 360° or one complete revolution. This configuration enhanced the consumed power of the driver and reduced the steering rate (Figure 20). In the hydraulic steering system, for a complete turn from the hard left to hard right, the steering wheel rotates about 4 revolutions. In

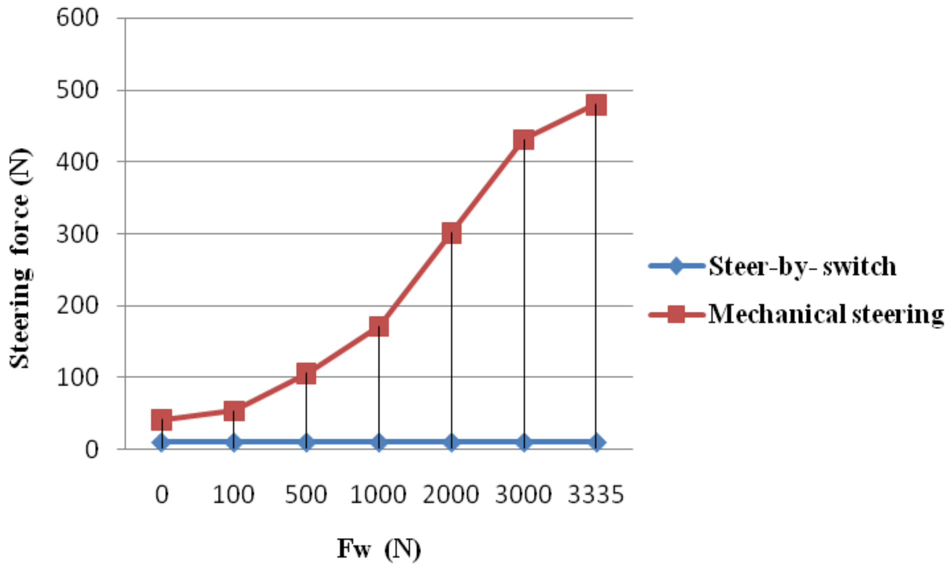


**Figure 19.** Relationship between the steering force and Fw in two steering systems.

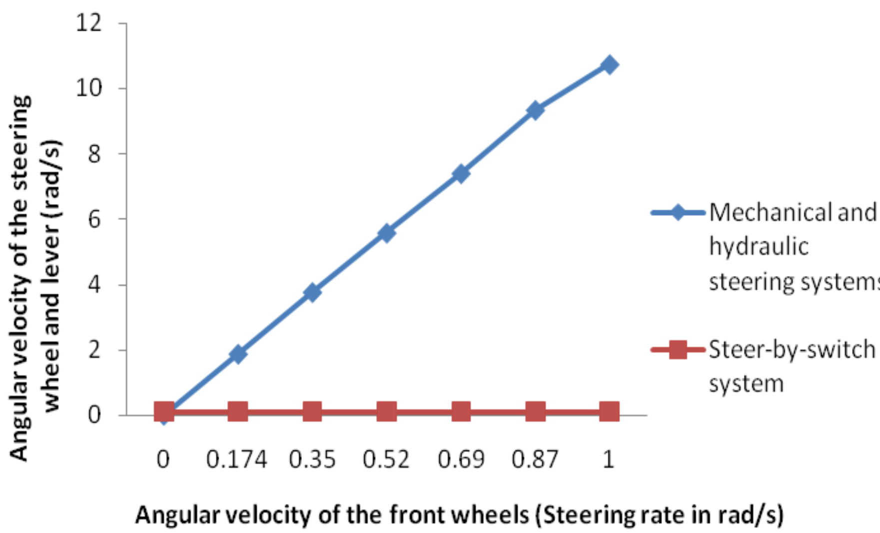


**Figure 20.** The relationship between $\dot{\theta}_l, \dot{\theta}_s$ and the steering rate ($\dot{\theta}_w$ ).

the steer-by-switch system, there was not any relationship between the angular displacement of the front wheels and the steering lever and for a complete turn to left or right, the steering lever rotated about 0.1 radians to press the push-button-switch (Figure 21). However, in this system, the steering rate could be adjusted by installing a volume control valve in the oil route to the hydraulic cylinder as shown in Figure 9. The limited angle of rotation of the steering lever and the low required force for movement of the lever diminished the consumed power of the driver and facilitated the steering process.

## Conclusions

To eliminate the detrimental effects of the steering wheel on drivers, a steer-by-switch method was proposed. In this method**,** steering of the vehicle is accomplished by two push button switches instead of a steering wheel. An electro-hydro-mechanical system is used to establish the connection between the switches and the front wheels.

The principle of operation resembles a full hydraulic steering system except for the lack of a steering wheel and utilization of an electrical system and photo sensors.

In this system, there is no mechanical connection

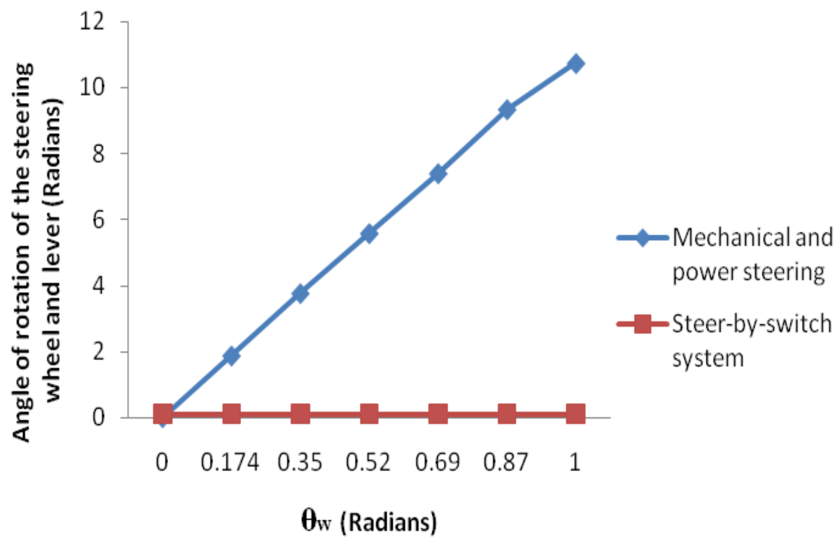


**Figure 21.** The relationship between the angular displacement of the front wheels and steering wheel or lever in 3 steering systems.

between the switches and front wheels. Therefore, the vibrations cannot be transmitted to the operator's hand from the wheels. This system is devoid of the hazards that threaten the safety of the operator due to the use of a steering wheel. In addition, it holds several advantages:

1) It provides flexible steering for the driver to control the vehicle from the desired location.
2) The required force for the operator to steer the front wheels is negligible.
3) This system is appropriate for invalid people who have a deficiency in one hand or have only one healthy hand.
4) The flexibility of the system due to the ability to displace the switch box allowing right and left-handed individuals to enjoy easy and comfortable steering. The flexibility of the system also allows for the remote steering of vehicles for robotic applications and utilisation of the vehicles in out of reach and hazardous environments.
5) The absence of a steering wheel, column, shaft and gear reduction mechanism simplifies the car interior design and allows much better space utilisation in the engine compartment.

This system is promising for future development and utilisation in high-speed automobiles.

**Nomenclature:** $\theta_l$ = Angle of rotation of steering lever; $\theta_s$ = angle of rotation of steering wheel; $\bar{a}_k$ = acceleration of tie rod; $\ddot{\theta}_s$ = angular acceleration of steering wheel; $\dot{\theta}_w$ = angular velocity of kingpin arm; $\dot{\theta}_s$ = angular velocity of steering wheel; $\ddot{\theta}_l$ = angular acceleration of steering lever; $\dot{\theta}_l$ = angular velocity of steering lever; $u_k$ = coefficient of friction between pinion and rack; u = coefficient of friction between tire and road; $F_p$ = force of pinion; $F_f$ = friction force on pinion and rack; E = Kingpin offset; $T_w$ = Kingpin torque; $r_k$ = length of kingpin arm; $\bar{I}_l$ = mass moment of inertia of the lever; $m_k$ = mass of steering axle; $\bar{I}_s$ = mass moment of inertia of steering wheel and steering rod; $\bar{M}$ = moment on steering wheel and lever; $m_s$ = mass of steering wheel; $m_c$ = mass of steering rod; P = power; $r_p$ = radius of pinion; $r_l$ = radius of steering lever; $r_c$ = radius of steering rod cross section; $r_s$ = radius of steering wheel; $F_w$ = required force for steering; K = spring constant of push-button switch spring; $F_d$ = the force applied to steering wheel by driver; $T_s$ = torque of steering wheel; $T_s$ = torque of steering wheel; $T_p$ = torque transmitted by pinion; W = weight of vehicle on steered axle; U = work of the system; $\bar{v}_k$ = velocity of kingpin arm; W = weight of vehicle on steered axle.

## REFERENCES


Aghkhani MH, Abbaspour- Fard MH (2009). Automatic off-road vehicle steering system with a surface laid cable: concept and preliminary tests. Biosyst, Eng., 103: 256-270.

Burstrom L, Lundstrom R (1994). Absorption of vibration energy in the hand and arm. Ergonomics, 37: 879-890.

Gescheider GA, Bolanowski SJ, Verrillo RT (2004). Some characteristics of tactile channels. Behav. Brain. Res., 148: 35-40.

Goglia V, Gospodaric Z, Kosutic S, Filipovic D (2003). Hand-transmitted vibration from the steering wheel to drivers of a small four-wheel drive

tractor. Appl. Ergon., 34: 45-49.
Gurram R, Rokheja S, Gouw GJ (1995). Mechanical impedance of the human hand-arm system subject to sinusoidal and stochastic excitations. Int. J. Ind. Ergonom., 16: 135-145.
Haasnoot RA, Mansfield NJ (2007). Effect of push/pull and grip force on perception of steering wheel vibration. In: proceedings of the 10th International conference on hand-arm vibration, Las Vegas, Nevada, USA, pp 7-11.
Kim JH, Song JB (2002). Control logic for an electric power steering system using assist motor. Mechatronics, 12: 447-459.
Kim JH, Jung SG, Kim KS (1985). An investigation of the steering wheel vibration and its reduction in passenger cars, Soc. autom. Eng., 912565: 961-968.
Morioka M, Griffin MJ (2009). Equivalent comfort contours for vertical vibration of steering wheels: Effect of vibration magnitude, grip force, and hand position. Appl. Ergon., 40: 817-825.
Proca AB, Keyhani A (1998). Identification of power steering system dynamic models. Mechatronics, 8: 255-270.
Pyykko I, Farkkila M, Toivanen J, Korhonen O, Hyvarinen J (1976). Transmission of vibration in the hand arm system with special reference to changes in compression force and acceleration. Scand. J. work. Envon.. Hea., 29: 87-95.
Reynolds D (1977). Hand-arm vibration: a review of 3 years' research, In proceedings of the International Occupational Hand-arm vibration conference, National Institute for Occupational Safety and Health, Cincinati: DHEW (NIOSH) publication, pp. 99-128.
Waard D D, Thigri GMPR, Bold VD, Evans B L (2010). Driver hand position on the steering wheel while merging into motorway traffic. Transportation Research part F: Traffic psycho. behav.. 13: 129-140.
Wang J, Wang Q, Jin L, Song C (2011). Independent wheel torque control of 4WD electric vehicle for differential drive assisted steering. Mechatronics, 21: 63-76.
Xue H, Wu H., Meng X, Liu W, Pan Z, Zhao F (2011). Simulation research and programming of torque fluctuation of automotive steering system. 2nd international conference on mechanic automation and control engineering, Inner Mongolia, pp. 10-11.