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Full Length Article

ECU controlled intelligent lift axle dropping and lifting system for heavy trucks

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ABSTRACT

This paper reports the design and control of an automatic lift axle auto-drop system that is normally controlled manually by the driver. The goal of the automatic lift axle dropping system is to drop or lower one or more of the liftable axles of the truck automatically, based on loading and other conditions. In this paper, the experimental implementation of an AutoDrop system in a truck suspended with a compensating arm type mechanical suspension is presented. Axle weight estimation for a compensating arm type suspension has challenges because of the articulated nature of the suspension mechanism and the presence of a large hysteresis characteristic. This paper introduces an analysis and higher accuracy height sensor based estimation method for weight determination in axles with a compensating arm suspension. An improved algorithm is developed and the lift axle system operation is automated to satisfy the rules mentioned in EU Directive 1230/2012 EEC. The developed algorithm is coded and implemented using an electronic control unit mounted in the vehicle cabin. Experimental results are used to demonstrate the successful implementation of the developed algorithm.

1. Introduction

Highway transportation using trucks is an important mode of transferring products/goods to their final destination. Highways are expensive investments that must be protected from wear due to vehicle operation. Commercial vehicles transporting heavy loads are an important contributor to the deterioration of the pavements on highways. One of the reasons of pavement damage is the overloading of heavy vehicles. This leads to excessive pressure on the road at the tire-road interface and eventually inevitable pavement damage.

Restoring the wear damage caused by overweight trucks requires huge capital investments and also reduces the capacity of traffic flow due to construction. The alternative approach of upgrading and rehabilitating the existing road network to make it capable of withstanding high stresses and tire pressures also requires a considerable investment [1].

There have been many studies investigating the effect of increased axle load on pavement performance, service life and maintenance costs. Early work by Yi [2] investigated the effect of active and semi-active heavy truck suspensions to reduce pavement damage. The road surface and truck endurance in Japan have been investigated by Kawamura [3]. Cole et al. [4] designed a truck suspension to minimize road damage.

According to a study performed by Salem [5], the maximum allowable axle load should not exceed 11 tons during the summer season and should not exceed 14 tons during the winter. According to the same Ref. [5], single axle loads greater than 14 tons should not be allowed even with a fine or penalty because this will result in a very quick deterioration of the pavement especially during the summer. Allowing the axle loads to be increased from 10 to 13 tons will reduce the design life of the pavements by half. The study by Hatipoğlu [6] indicates that lowering the legal weight limit than can be supported by a single axle from 13 tons to 11.5 tons results in a corresponding increase in the durability of the highway pavement by up to 32%.

This paper presents an automatic lift axle dropping and lifting system to help improve the pavement life and to adhere to the legal per axle weight and weight distribution limits. The aim of an automatic lift axle dropping system is to drop the appropriate axle(s) automatically based on the loading condition, instead of being manually controlled by the driver as illustrated in Fig. 1.

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Nomenclature

ECU	electronic control unit
CAN	controlled area network
CCP	CAN calibration protocol
TCS	traction control system
RAL	rear axle loading

Fig. 1. ECU Controlled Axle Lift/Drop system.

The axle-lift device is used by drivers to raise the axle in order to reduce fuel consumption, tire wear and provide easier take off on slippery surfaces.

The lift axle dropping system is expected to be a legal obligation for all heavy commercial trucks operating in Turkey in 2020. According to the EU Directive 1230/2012 EEC Mass and Dimensions Policy, the manufacturer must ensure that under all driving conditions, the mass corresponding to each axle or axle groups must be within permissible limits except when taking off on slippery surfaces.

The important parts of the EU Directive Mass and Dimension Policy 1230/2012 [7] as given on 21.12.2012 are outlined below as design requirements for the automatic axle lift/drop system presented in this paper.

If a vehicle is fitted with one or more lift or loadable axles it shall be ensured that under normal driving conditions the registration/in-service maximum permissible masses on solo axles or groups of axles are not exceeded. To that end, the lift- or loadable axle(s) shall be lowered to the ground or be loaded automatically if the nearest axle(s) of the group or the front axle(s) of the motor vehicle is/are laden to its/their registration/in- service maximum permissible mass(es).

Where a lift axle is in elevated position, it shall be ensured that the mass on the steering axle(s) continues to be sufficient to ensure the safe driving of the vehicle under all circumstances. For such purposes, the vehicle manufacturer shall specify, in the case of incomplete vehicles, the minimum mass on the steering axle(s).

By way of derogation from the requirements above and to help motor vehicles or vehicle combinations to move off on slippery ground and to increase the traction of the tires on these surfaces as well as to improve their maneuverability, the axle lift device may actuate the lift- or loadable axle(s) of a motor vehicle or semi-trailer to increase or decrease the mass on the driving axle of the motor vehicle, subject to the following conditions:

(a) *the mass corresponding to the load on each axle of the vehicle may exceed the maximum authorized mass on the axle in force in the by up to 30% provided it does not exceed the value stated by the manufacturer for this special purpose.*

(b) *The mass corresponding to the remaining load on the front axle (s) shall remain above zero (i.e. in case of a rear loadable axle with long rear overhang, the vehicle may not tip up).*

(c) *The lift- or loadable axle(s) shall be actuated only by a specific control.*

(d) *After the vehicle has moved off and before its speed exceeds 30 km/h, the axle(s) shall automatically be lowered again to the ground or be reloaded.*

Although, there are a couple of systems that satisfy all of the above obligatory rules on air suspension mounted axles, there is no implementation on mechanically suspended trucks with tag axle around the world. In Europe, where 1230/2012 EEC is already legislated, all retractable axle fitted vehicles are equipped with air suspension systems. However in Turkey, heavy commercial trucks that have mechanical suspension systems are quite popular as they can have a much larger cargo weight capacity.

This paper presents a control mechanism that senses the axle loads and lowers the retractable axle automatically if the nearest axle or axle groups exceed the limits for mechanically suspended trucks with compensating arm type suspension in order to prevent pavement damage. An overview of the algorithm and associated simulator developed for heavy commercial trucks with mechanical suspensions are presented along with work on mass production of the proposed system for a series production truck.

The organization of the rest of the paper is as follows. Conventional axle lifting systems are introduced in Section 2. The mechanical and mechatronic design of the system based on the design requirements outlined above will be explained in Section 3. The structure of lift axle mechanisms and boundary diagram for an automatic lift axle system will be introduced. All algorithm inputs except the axle loads are already available on the vehicle CAN bus with the J1939 protocol. The algorithm is designed for meeting the requirements in the EU Directive 1230/2012 EEC Masses and Dimensions Policy. In Section 3, the algorithm development in a simulator setting is presented. The algorithm is coded in Simulink [6] and is validated using the TruckMaker virtual truck simulation program by defining a generic truck that has $8 \times 2S$ axle configuration with two liftable axles. The axle loads are obtained from this virtual Truckmaker truck model during the simulations. During the simulations, the condition of the truck's load is used as an input and the automatic lift axle system algorithm decides on the axle(s) that should be dropped. The algorithm uses a state-flow chart. Weight estimation for axles with compensating arm type suspension using height sensors is introduce and improved to result in higher accuracy. In Section 4, the developed algorithm is implemented in an actual truck and evaluated experimentally. Section 5 concentrates on extension to series production. The paper ends with conclusions and suggestions for future work.

2. Conventional axle lifting system

A pneumatic axle lift/drop system such as the one shown in Fig. 2 comprises of an air compressor, pistons/bellows, valves and mechanical coupling elements. The air compressor provides pressured air to the pistons/bellows in order to push or pull the axle to position it in either its lifted or lowered condition. Valves control the airflow between the pistons and the air compressor and are also used for exhausting the air from the pistons/bellows.

Let us consider a mechanically suspended truck with an 8 × 2S axle. This truck has two liftable axles, as indicated by the arrows in Fig. 3. Those axles have different lifting mechanisms but both are controlled in the same manner.

In manual usage, solenoid valves are controlled by switches mounted in the instrument panel in the truck cabin. In order to lift/drop the axle, the driver pushes the corresponding switch and the axle is actuated directly, regardless of the vehicle condition.

The tag-axle lifter mechanism is used for lifting tag axle, which is third axle for 6 × 2 trucks, and fourth axle for 8 × 2 trucks. System is supplied with a solenoid valve triggered by its coil. Since system should control and observe the status of tag axle position (up-down/lifted-dropped), solenoid valve rate current/voltage and lift/release time of axle movement is important. When lift button is pressed, solenoid valve is triggered and allows airflow through lifter below, and axle will be lifted through system kinematics, with u – bolts.

Although the driver controlled axle lifting/dropping is quite advantageous, in many cases, it is either not used or misused.

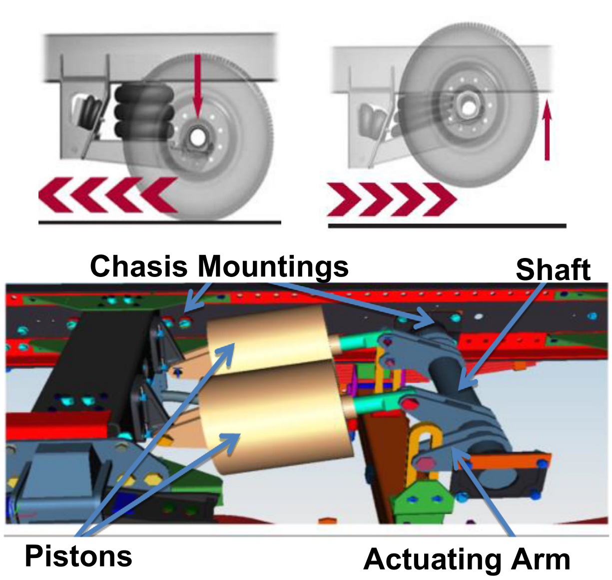

Fig. 2. Truck Axle lifting mechanisms.

The drivers sometimes simply ignore to use the system. In some cases, the system is not being used since loading conditions are not obvious to the driver. In many cases, even when the loads require the dropping of one or two axles, the drivers do not carry this out in order to reduce tire wear. The lifter mechanism works regardless of any other condition except driver intervention via lift switches. The axles can be at their lifted position even when the truck is fully loaded which may lead to damage.

The misuse of the axle lifting mechanism may lead to damages to the road pavement and/or vehicle itself. In order to prevent these issues, Mass and Dimension Policy 1230/2012 describes the automatic lift axle drop system in its Annex IV.

3. Automatic lift axle system design

An automatic lift axle lifting/dropping system aims to automate the dropping action. It aims to lower damages to the truck, as well as damages to road pavement due to loading conditions. The system also helps in increasing traction when the road surface is wet or icy. By automating the system, the task of deciding when to lift or drop the axles will no longer be a burden to the driver.

In this section, the mechanical and mechatronic design of the system based on requirements are presented. An 8 × 2S vehicle is analyzed, as it is the worst case in terms of axle configuration. The proposed system will be more beneficial to such a truck. The AutoDrop system introduced in this paper involves an electronic control unit to actuate solenoid valves. All environmental components, e.g. switches, lift axle solenoid valves and sensors, are connected to this control unit and axles are actuated by the algorithm running inside it (Fig. 4).

3.1. System requirements and algorithm

The main requirement for the AutoDrop system is the measurement of axle loads. The system must drop the appropriate axle(s) automatically based on the loading condition in Table 1.

If the second axle is lifted and if the rear axle group load exceeds 18.0 tons, the system will drop the nearest axle, which is second axle, in order to share overload and maintain axle loads under permissible limits and does not allow driver to lift axles again. Other conditions that do not involve axle loads are also included in the regulation in addition to the conditions given above. For instance, once ignition is off, all axles should be lowered. Speed limit is taken into account for functional requirements to provide safety driving by disabling any driver input above 30 kph. Additionally, in order to improve emergency brake performance when parking brake is engaged tag axle (4th axle) should be dropped or not allowed to be lifted by driver since wheels should be in contact with the road surface. An algorithm that satisfies all necessary requirements designed using the input/output list in Table 2.

Considering a truck with 8 × 2S axle configuration, there are two liftable axes (2nd and 4th axes). A flowchart of the proposed algorithm is presented in Fig. 5. The algorithm starts with start button. It checks whether ignition is turned on or not, as well as the axle positions. If the vehicle is not running, it will automatically drop axle 2. If the vehicle is running, it will check the rear axle load (RAL) value agains 18 tons. This information is used to determine the state of axle 2. If the RAL is lower than 11.5 tons, then axle 4 will be lifted.

State-flow chart is designed as shown Fig. 6. The conditions Q0, Q1 and Q2, represent the three different positions where the axles can be placed [8]. State transition conditions are defined according to functional requirements declared in this section. As an addition to the previous study in Keleş et al. [8], each state has its own

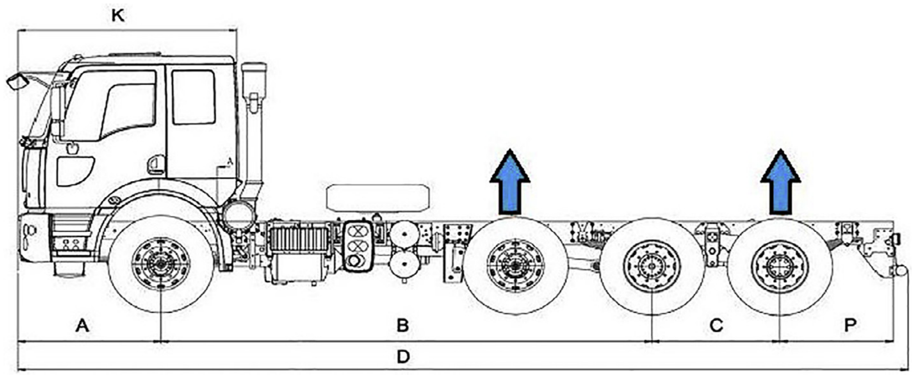

Fig. 3. Mechanically suspended truck has 8 × 2S axle configuration with two liftable axles.

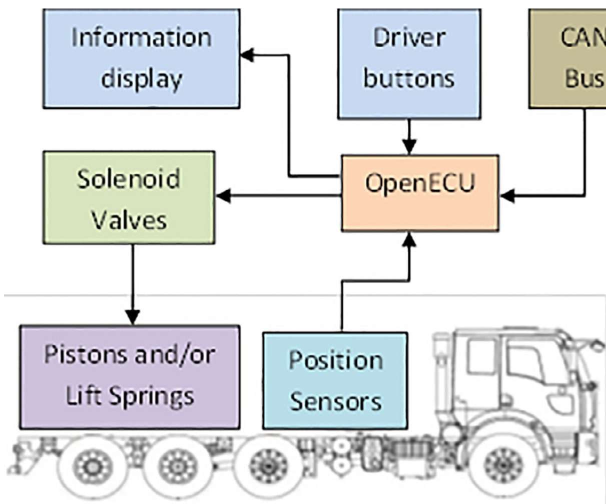

Fig. 4. Proposed Automatic Axle Lifting System.

sub-routines where detailed axle information e.g. axle is being lifted, axle cannot be dropped, axle cannot be lifted are stored.

In the state-flow chart, Q1 indicates that second axle is lifted and fourth axle is dropped. Parameter '×3' is the set of transition conditions in order to lift fourth axle and are defined as:

- Front axle load should be below 7.1 tons,
- Rear group axle load should be below 11.5 tons,
- Parking brake should be released,
- Vehicle speed should be below 30 kph and
- Ignition should be ON.

3.2. TruckMaker simulation

It can be seen from Table 2 that all the inputs but axle loads are available in a vehicle for implementation purposes. Assuming that the axle loads can be derived correctly, the designed algorithm will be tested in a simulator first. The vehicle simulation program TruckMaker is used to model the truck, its environment, driver maneuver and driving scenarios. Simulink is used to implement the algorithm and send the driver inputs and axle movement commands to the TruckMaker vehicle model. TruckMaker and Simulink are co-simulated in the near real-time (soft real-time) simulation mode of Truckmaker, which is a great advantage because the same algorithm codes written in Simulink can also be used in the electronic control unit used in the experimental truck.

Lift/Drop axle is not defined in TruckMaker as a function. Thus, to simulate proper axle movement and axle load distributions, the vertical axes of tires are altered in software by using a discrete integrator. System input and outputs are re-organized to match TruckMaker parameters as displayed in Table 3.

3.3. Axle load calculation

The basic function of the AutoDrop system is to generate the appropriate control signal according to axle loads and positions. Thus, axle load must be estimated in order to construct an implementable system. This can be achieved by measuring the deflection of springs. In other words, the distance between axle and chassis arm can be measured using deflection sensors. The set up consists of an 8 × 2 self-steer vehicle as a worst case vehicle type, displacement sensors mounted at different positions on each axle, an OpenECU from Pi Innovo used to test algorithm and data collection, weight pads to determine the corresponding wheel load of the axle as shown in Fig. 7. Mass estimation models are trained for each individual axle in order to find the correlation between axle load and deflection sensor outputs. The axles considered are the front-steering axle and the rear axle group called the tandem axle unit as drive axle and tag axle are interconnected with a compensating arm type suspension.

3.3.1. Front axle suspension load

Front axle's leaf springs are single mounted springs and have linear load-deflection correlation that have relatively smaller hysteresis difference between loading and unloading states at a value of approximately 250 kg. In interpreting the results like that in Fig. 8, front axle mass estimation model can be extracted using conventional methods using:

$$G_{front} = a v_1 + b \tag{1}$$

Table 1
Permissible Axle Loads Declared in Masses and Dimensions Policy.

Vehicle Condition	1st Axle	2nd Axle	3rd Axle	4th Axle
All axles are on ground	7.1 ton	25.0 tons (sum of rear axle weights)		
2nd axle is lifted	7.1 ton	–	18.0 tons	
2nd and 4th axles are lifted	7.1 ton	–	11.5 tons	–

Table 2
AutoDrop System Input/Output Signal Parameters, Types and Descriptions List.

Parameter	Signal	Description	Type
Axle Loads	Analog	Load input for each axle	Input
DR_A2	Digital	2nd axle lift/drop button input	Input
DR_A4	Digital	4th axle lift/drop button input	Input
Ignition	Digital	Ignition ON or OFF status	Input
ECU_A2	Digital	2nd axle lift/drop actuation signal	Output
ECU_A4	Digital	4th axle lift/drop actuation signal	Output
A2_SIG	CAN Tx	2nd axle liftable/not liftable info	Output
A4_SIG	CAN Tx	4th axle liftable/not liftable info	Output
Hold_PSU	Digital	Hold Power Supply Unit even if Ignition is OFF	Output
pbrake	CAN Rx	Parking Brake information	Input
v_speed	CAN Rx	Vehicle Speed information	Input

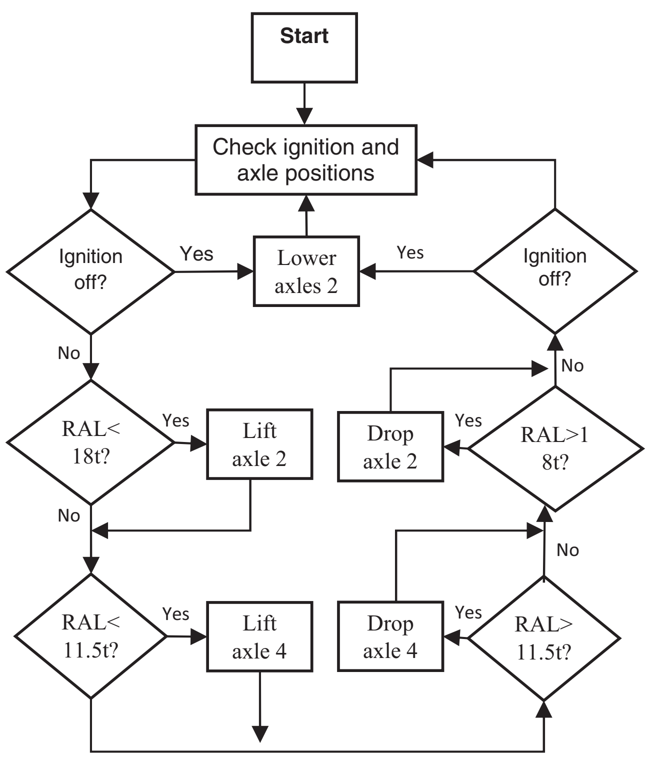

Fig. 5. Flow chart of the algorithm.

In Eq. (1), v_1 refers to deflection sensor output signal attached to corresponding axle. In order to find front axle load, G_{front}, a and b are found as 1429 and 64.08 with experimental studies by collection of training data and curve fitting. Once the coefficients are found, the axle load can be estimated by just using the deflection sensor in online-tests.

3.3.2. Rear axle compensating arm type suspension load

The mechanical suspension mounted trucks generally have interconnected axles on rear axle groups to share the load appropriately on rough roads and the geometry should be adequate in order to balance the load transfer between the axle groups according to the axle capacities. The tandem axle unit as rear group axle's mass estimation model is the challenge here because of drive axle and tag axle that are the elements of tandem axle unit connected each other by a balancer. Therefore, their displacements affect each other and correlation between load and deflection is determined using Eq. (2).

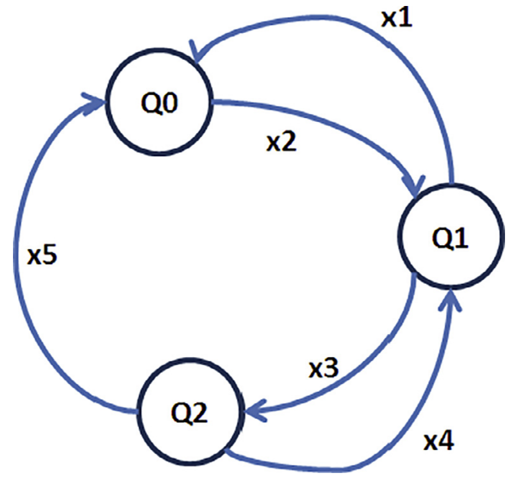

Fig. 6. System State-Flow Chart Macro View.

Table 3
TruckMaker Input/Output Signal Parameters, Descriptions and Data Names List.

Parameter	Signal	Description	Data Name
G1	Read	Front Axle Load	Car.SpringFx.Frc
G2	Read	2nd Axle Load (Self Steer)	Car.SpringFx2.Frc
G3	Read	3rd Axle Load (Drive Axle)	Car.SpringRx.Frc
G4	Read	4th Axle lift/drop button input	Car.SpringRx2.Frc
Brake	Write	Brake Pedal	DM.Brake
Clutch	Write	Clutch Pedal	DM.Clutch
Ignition	Read	Ignition Information	DM.EngineSwitch
Gas	Write	Gas Pedal	DM.Gas
AxlePos	Write	Axle Lift/Drop z-position	Car.CFxx.tz_ext

Fig. 7. Training Data Collection Tests (Axle Loads and Sensor output).

$$G_{drive} = f v_3 + g v_4 + h \quad (2)$$

where v_3 and v_4 refer to sensor outputs connected to drive axle and tag axle which are elements of the compensating arm type suspension. A typical function fit and its comparison to the one input function fit are shown in Fig. 9.

For mass estimation model training especially for tandem axle unit many different vehicle scenarios were tried on each loading condition and nearly 90 different loading conditions in different sequences were used in test specification. The mass distribution characteristics were identified from the combination of vehicle and loading cases. The pre-defined mathematical function parameters are optimized according to collected training data as 4951, 6324 and −28,880.

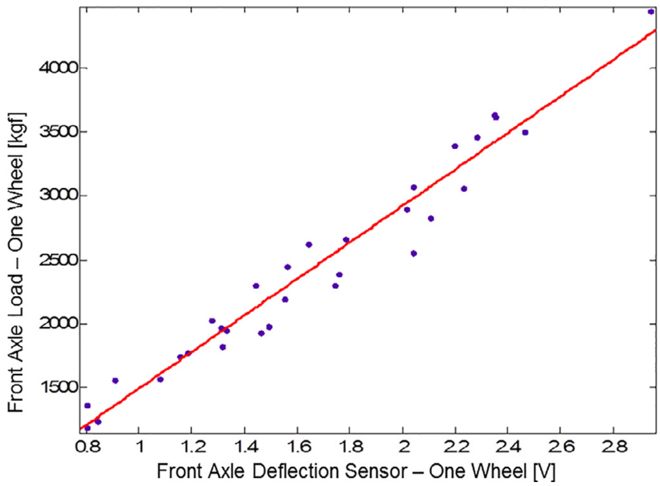

Fig. 8. Front Axle Load Linear Function.

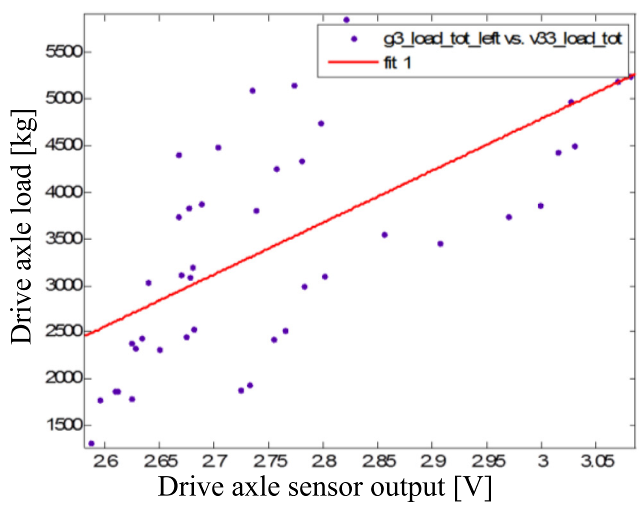

Fig. 9. Axle Load Estimation model obtained using sensor on the tandem for.

4. Integration to a vehicle and experimental results

The design of the axle-drop system based on functional requirements was completed on the previous section. This section introduces the implementation of the subsystems to the vehicle and successive tests and results.

Online axle load calculation is made by entering the axle load function parameter in a simple program. The AutoDrop system algorithm developed for the 8 $\times$ 2S test truck runs in a PI INNOVO M250 ECU module using Matlab/Simulink [9] as the software development platform a. ECU parameter calibration and embedded program variable monitoring is provided with ATI VISION based on CCP (CAN Calibration Protocol) (Fig. 10).

The main principle of the algorithm is to determine the authorization assignment between ECU and driver about lift/drop command on retractable axles. Two indicators in the cluster (red circles in Fig. 10, refer to Table 2. A2_SIG and A4_SIG) convey the authorization state to the driver. The vehicle is instrumented with the OpenECU electronic control unit, break-out-box and relay circuit. All I/O s are connected to the ECU through the break-out-box and solenoid valves are driven by relay circuits as shown in Fig. 11.

The function fit variation reduced to 489 kg with the newly proposed method of Eq. (2) while in the conventional method this value was up to 2 tons. With the proposed load estimation function, mass estimation error is found as 450 kg for front axle. For compensating arm type suspension load estimation performance, to cover worst case, improper 28 loading scenarios has been applied and error is found as 760 kg near design region, which, in fact, is a permissible axle load limit. The algorithm presented here

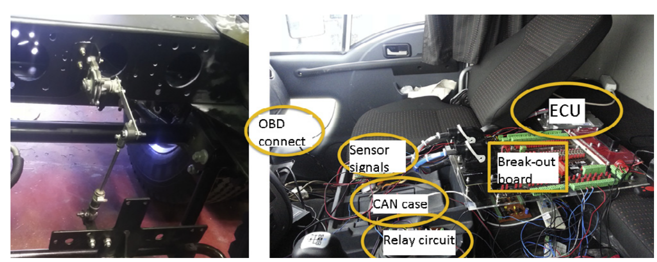

Fig. 11. Sensor assembly (left) and Electronic Circuit Layout (right) in cabin.

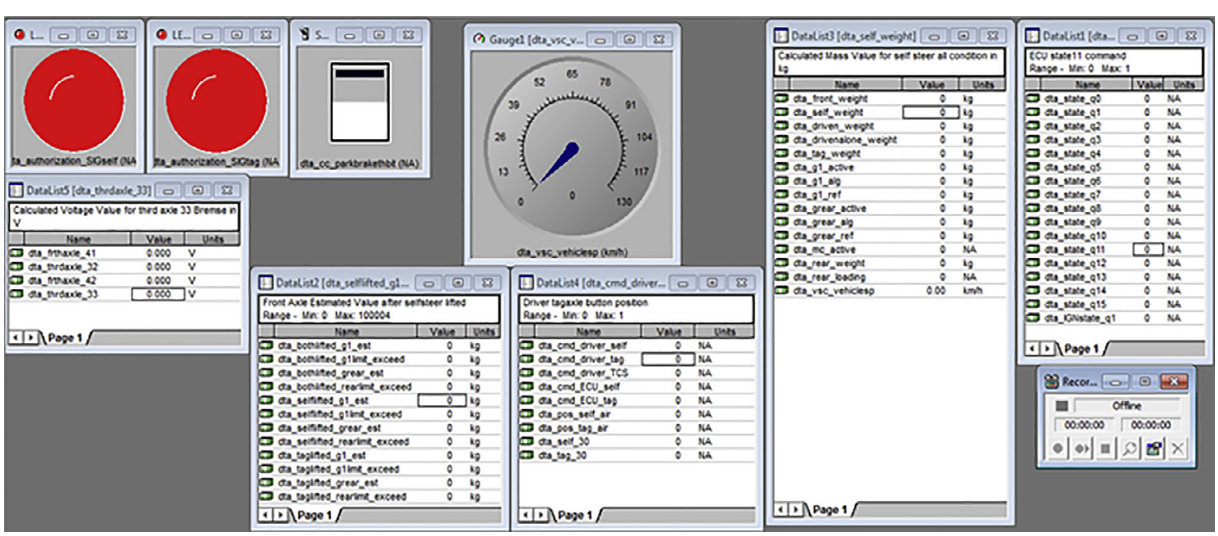

Fig. 10. System Parameter Monitoring with ATI VISION by using CCP.

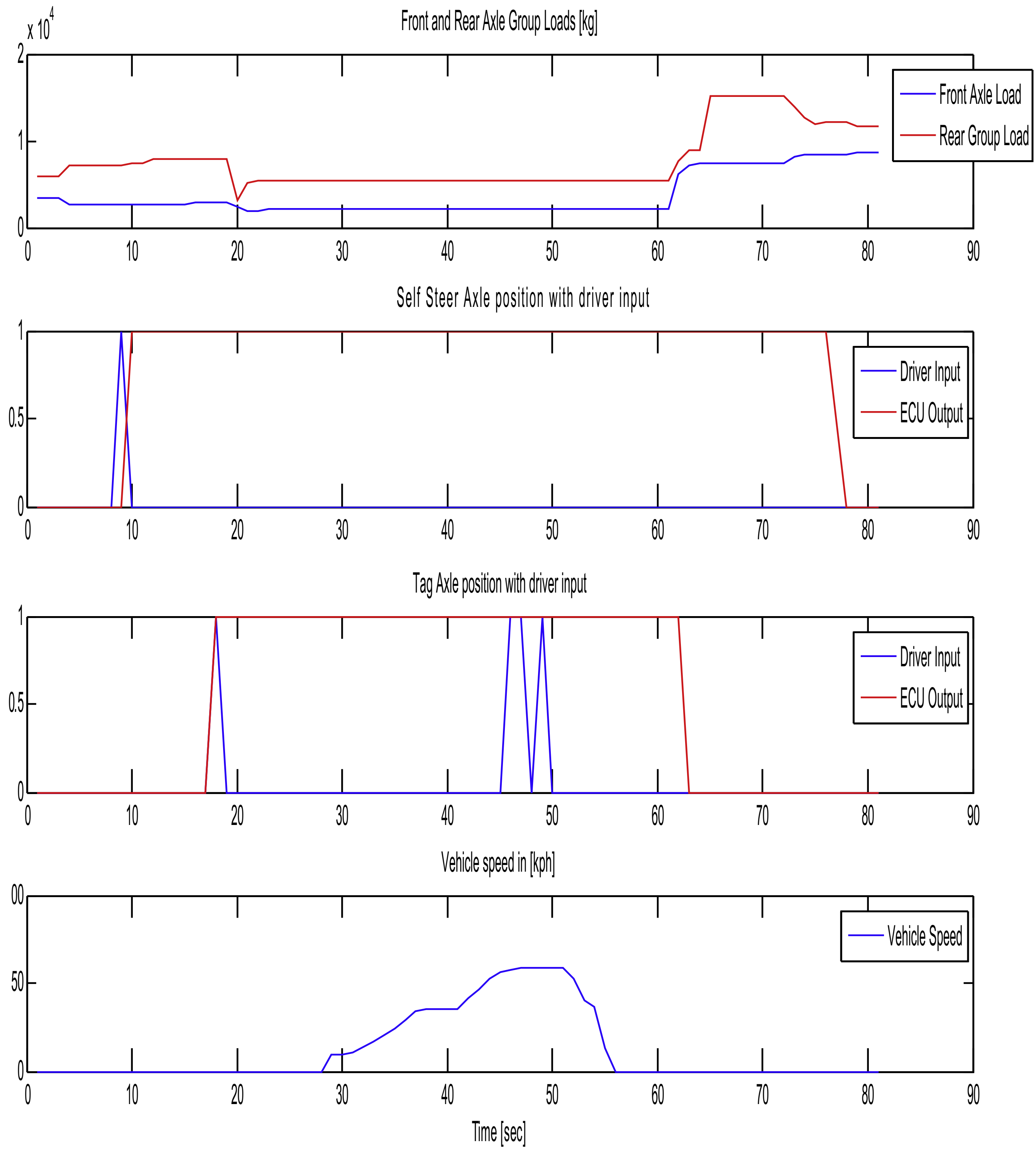

Fig. 12. Algorithm Test Scenario.

results in satisfactory results in an actual in-vehicle implementation.

The developed algorithm is tested under a large variety of possible situations one of which is displayed in Fig. 12. Initially vehicle is not loaded. Drivers command of lifting both of the axles are accepted by the algorithm. In the 45th second, the tag axle-dropping request from driver is neglected because the vehicle speed is over 30 kph. After the vehicle is stopped around 60 s, the vehicle is loaded. Both of the axles are automatically dropped in order by the algorithm.

5. Series production

In 2016, the auto-drop functionality proposed in this paper went into series production of a truck manufacturer. The general view of the system layout is shown in Fig. 13. The most critical part of the system is the axle load estimation for compensating arm suspension by using a sensor network. The system involves an FODP2 Diagnostic Program, to have easy Sensor Calibration, Parameter Configuration and DTC Read/Delete ability.

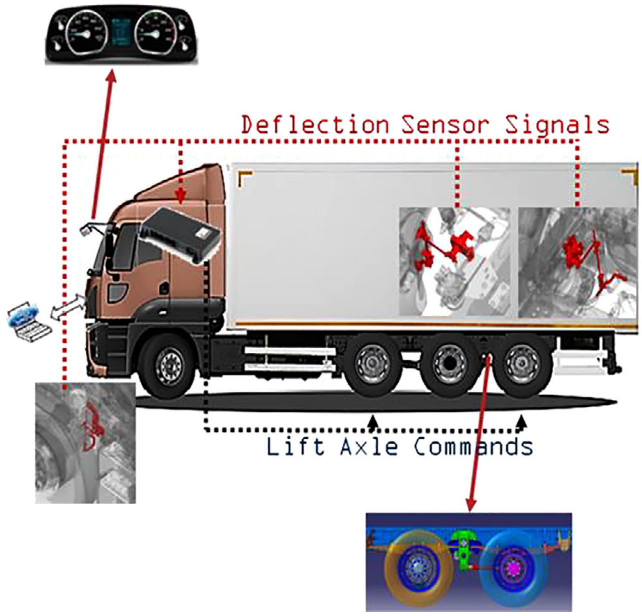

Fig. 13. Developed system overview.

The system considers axle load limits, checks ignition and parking brake conditions. It provides traction assistance when needed and consider speed limits as needed. A supervisory controller is used for implementation of these functions. The lift axle system has two user switches (tag axle and self-steer) on IP in order to send lift/drop request to the ECU algorithm (Fig. 14).

A cluster screen has been placed on the driver information screen as shown in Fig. 15 to provide relevant information to the driver. The driver can get information about axle states, request refusals (if any), automatic actions and failures.

With this work presented here, an automatic tag axle dropping system has been developed for mechanically suspended vehicles for the first time.

Integrated axle weight measurement via electronic sensors has been developed in mechanical suspended vehicles with tag axle lifting feature for the first time. This involved the hysteresis detection and correction functionality. It involved load estimation on compensating arm type suspension vehicles that may or may not have tag axle lifting. The system is compatible to estimate drive axle load even when the tag axle is in the lifted position. In this case, the compensating arm becomes outranged and chassis level increases when tag axle is lifted even though the load increases on the driven axle.

Axle load estimation error per axle was decreased to 0.4 tons from 2 tons compared to conventional methods. By ensuring that the axle loads remain within permissible limits, service maintenance costs are reduced. The system provides better braking performance and safer driving practice. The system also enabled the transmission of vehicle weight data to the Electronic Brake System

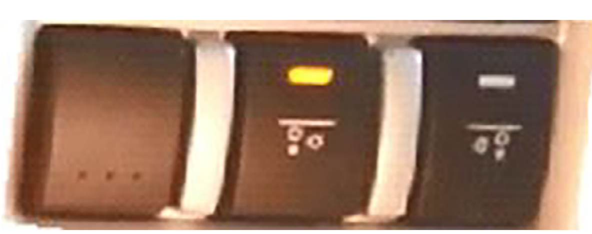

Fig. 14. User input switches for axle dropping system.

Fig. 15. Screen for the axle dropping system.

(EBS) of the vehicle with higher accuracy. Tag axle Lift/Drop function is connected to the Parking Brake in order to activate parking brake actuators located at the tag axle. Additional features such as traction help, reverse gear maneuver improvement, online damage model etc. can also be included.

The use of a readily available, body controller unit eliminated the need of additional ECU. This approach decreased the cost. It is expected that about 3000 heavy trucks per year can be sold at the EU and Turkish markets where the regulation is mandatory. The end result is a considerable improvement on road pavement performance by preventing axle (and tire) overload.

6. Conclusion

In this paper, a lift axle dropping system for road trucks with mechanical suspension was presented. The proposed algorithm is designed according to this principle and the functional requirements of the system. Simulink was used for algorithm development and implementation and TruckMaker was used for modeling. The aim was to make the system compatible to all mechanically suspended trucks, thus a load estimation method is proposed for compensating arm type suspension.

The main challenge was that axle load estimation has never been done before for compensating arm type suspensions. The conventional methods for single leaf spring suspensions resulted in very low accuracy for the compensating arm type. The designed Auto-drop system was implemented successfully on an $8 \times 2S$ prototype truck. It can drop/lift the appropriate axles based on the conditions given in the algorithm without any input required from the operator. In 2016, the auto-drop functionality went into series production and Ford Trucks Turkey implemented this system on some of its trucks successfully.

The contributions of the paper are as follows:

- Automatic tag axle dropping system has been developed for mechanical suspended vehicles for the first time.
- Integrated axle weight measurement via electronic sensors has been developed in mechanical suspended vehicles with tag axle lifting feature for the first time.
- Axle load estimation error per axle was decreased to 0.4 tons from 2 tons as compared to conventional methods.
- By ensuring that axle loads remain within permissible limits, service maintenance costs are reduced.
- The system enabled the transmission of vehicle weight data to Electronic Brake System (EBS) with higher accuracy.
- Tag axle Lift/Drop Function is connected to Parking Brake in order to activate parking brake actuators located at tag axle.

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