Energy Harnessing from Bus Rapid Transit Vehicles through Deformable Speed Bumps: a Case of Dar es Salaam BRT System, Tanzania

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Abstract

Bus Rapid Transit (BRT) system is an effective way of commuting passengers in cities. This study investigates possibility of harnessing energy from weights of the bus rapid transit vehicles. An experimental method was used on a testing set consisting of fluid power devices to simulate movements of loaded buses approaching the passengers' stations. Buses weighing between 7-9 tons and moving at speed range of 10-25km/h were deployed. A hydraulic accumulator was used to store the energy converted from the vehicle weights through a hydraulic system located under a deformable speed bump. The BRT buses used in Dar es Salaam were used in capturing their weights for that purpose. Results indicate that with the speed bump proposed for BRT buses, weights can be converted into energy through hydraulic accumulators. Under minimum operating conditions, the deployed buses could generate 190.67 kJ after every 57 tyre passes over the bumps.

Keywords: BRT buses weights, Hydraulic accumulator, Energy, Transport.

Introduction

Power transmission can be achieved through three fundamental means; these are electrical, mechanical and fluid (El-din & Rabi, 2009).The study has concentrated in the fluid power transmission mode, where a suitable fluid power system was designed and incorporated underneath a speed bump. The speed bump is of a deformable nature where it protrudes over the road just like other bumps when no vehicle tyre presses on it, but deforms when a vehicle passes over it.

There are springs to retain the bumps into the protruded position after the passage of each set of the vehicle tyres. A hydraulic system embedded underneath the bump is used to suck hydraulic oil from nearby reservoir as bump moves up and confine the oil into hydraulic accumulators as the bump is pressed on. The process goes on until the pre-set pressure value at the accumulators is reached after which the latter releases the oil under pressure. This oil drives a hydraulic motor which executes the required mechanical power. The study aims at covering this research gap where vehicle weights are left untapped while if properly harnessed the weights can be converted into valuable entity.

It should be noted that movement of the speed bump is due to the weights of the passing vehicle. The hydraulic system in this case has been used as an energy conversion mechanism, where weight has been converted into hydraulic pressure in the accumulators and ultimately converted into mechanical energy at the hydraulic motor.

The aim of the speed bump system employed in this study, therefore, is to help in trapping the weights of the buses operating under the Dar es salaam Bus Rapid Transit System and converting them into mechanical energy for useful applications.

Research Problem

The buses operating under the Dar es Salaam Bus Rapid Transit Systems, Figure 1, are among large vehicles carrying a large number of passengers on land-based mode of transport. As such, this research aims at converting the total weights of these buses into useful energy through a fluid power system mounted on a specially built road bump system and use the trapped energy for various applications.

Figure 1: Dar es Salaam UDART buses
(***Source:*** Rweyemamu, 2016)

In this study, therefore, an experimental set up was used to test the possibility of acquiring energy from weights of bus rapid transit vehicles by modifying the conventional speed bumps into deformable platforms, install an energy conversion system on the platforms and apply the proposed system to land based transport vehicles and UDART buses. The experiments conducted also served in studying whether the hydraulic system can be used as an efficient energy conversion system in this particular case. The energy so generated can be used close to where it is generated like illuminating and ventilating the bus stops, extraction of exhaust gases out of urban tunnels, as well as irrigating nearby city gardens. It can also be used to drive various electric powered equipment including road side elevators for elders and disabled people, or even power road side billboards for advertisements.

City municipalities and road construction agencies in many countries have been imposing speed bumps and barriers on critical sections of the roads to control traffic and guarantee safety of other road users beside the drivers and their passengers. Although complained by some drivers, studies show that speed bumps constitute an effective means of controlling over-speeding of vehicles (Ashdown *et al* 2012: Antic *et al.* 2013).

Speed bumps also help awakening long distance drivers especially those travelling during the night by creating minor discomforts to the drivers when their vehicles hit the bumps (Fig. 2).

Figure 2: Conventional speed bump
(***source:*** Nulinukas, 2021)

Literature review

The idea of deformable speed bumps is not new as there are few patents already available on the issue. In 1994, Benjamin Beveridge filed a patent with application number 9407145.3 describing his invention of a deformable speed bump (Beveridge, 1994).

A Spanish firm Badennova is known to have developed a prototype of an intelligent speed bump BIV as seen in Figure 3 which uses fluid that changes from being soft and hardens when a vehicle exceeds the established maximum speed (World Highways, 2021).

In another patent, Graham Heeks applied for a U.S patent number US 09/990, 409 for his patent describing a speed bump composed

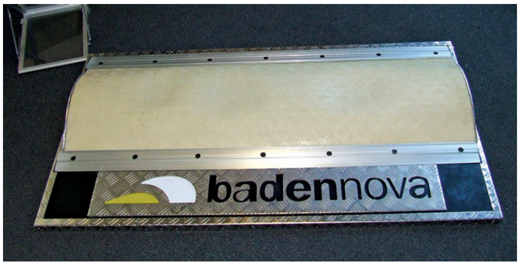


Figure 3: Deformable road bump
(***Source:*** World Highways, 2021)

of resilient materials that enable it to deform in order to allow passage of slow-moving vehicles and become stiff when a set speed is exceeded (Heeks, 2003). Similar work was also conducted in a research where articulated platforms were used as speed humps to house a flywheel mechanism underneath for the purpose of generating electrical energy from vehicle weights passing over the platforms (Philips, 2009). Other researchers that investigated speed bumps as a means of power generation include (Ramadan *et al.,* 2015) where they investigated different types of speed bump power generating systems.

Another study involving speed bumps was conducted by Watts and Krylovin (2000) which ground-borne vibrations resulting from vehicles passing over road humps were studied. The researchers also investigated effects of those vibrations on nearby buildings. They established vehicle models and by using previously obtained traffic data as guidance, they took measurements of the vibration levels induced.

All the patents on speed bumps encountered so far, have described the same purpose which is restricting the speeds of vehicles. This study, however, has concentrated on incorporating an energy conversion mechanism (the deformable road bump) so that whenever a vehicle passes over the bump, energy will be generated and stored for different uses. Although the proposed system in this study does not strictly set the speed limit, low speeds commonly encountered in conventional speed bumps are expected. The energy generated can even be fed into the grid and used in smart charging systems for electric vehicles.

Materials and Methods

This section deals with the materials and methodologies employed in conducting this research. The study is mostly based on experimental analyses. However, some review and statistical data were also collected in achieving the research goal. The section covers several aspects of the materials and methods including explanation on the proposed speed bump system, description of the experimental set, the way energy conversion takes place and energy analysis. The experimental analysis starts at the speed bump shown in Figure 4. The proposed speed bump system in this study consists of a platform (1), a series of hydraulic cylinders (2), compression springs (3), hydraulic valves and fittings (4), supporting base (5), hydraulic accumulators (6), hydraulic tank (7) and a hydraulic motor (8).

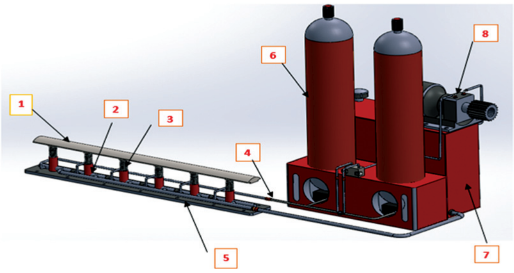


Figure 4: Proposed deformable speed bump system

The proposed speed bump energy conversion system can be located at ideal places where the energy generated therein can be used. These locations include commuter bus stops, BRT passenger boarding stations, entrances and exits of urban road tunnels, around overhead viaducts, road-railway crossing junctions and near steep corners.

The Experimental Set up

In order to simulate and analyse the possibility of using speed bumps as a means of generating energy from weights of vehicles passing over, an experimental set up given in Figure 5 was used. The set up consists of a pressing cylinder (1) which imitates the pressing force of a vehicle (weight exerted on tyres) when pressing over the road bump. When the first set of tyres has passed, the bump raises under the spring force thereby sucking oil from the hydraulic reservoir (5). The bump is kept upright by a small hydraulic cylinder (2) which sends small amount of oil into the accumulators (3) as the second set of tyres presses. The oil sent is prevented to return to its original path by a check valve. The oil is filled there until the set pressure is reached, then the oil which is now under high pressure is allowed to exit through another path to the hydraulic motor (6) and drive it thereby converting hydraulic energy into mechanical work. In real application, the oil is forced into the accumulators by the vehicle weight, but on the experimental set, movement of the filling cylinder (2) is done with the help of the hydraulic power unit (4) which contains pump inside the small tank and that is driven by electric motor seen on the power unit.

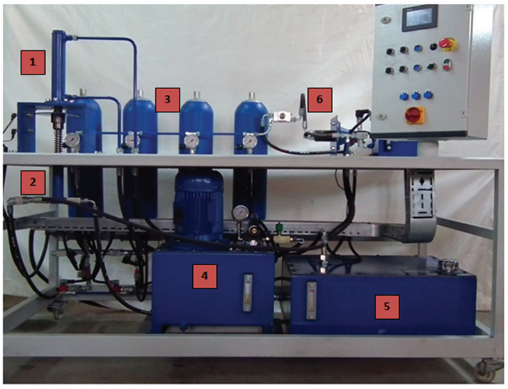


Figure 5: Experimental set up used in the study
(***Source:*** Khalfan & Imrek, 2015)

How Does the System Work?

The experimental set up reflects the proposed energy conversion mechanism under a deformable speed bump. Idealisation of this system in practice is as decribed below:

The deformable speed bump consists of a series of short stroked hydraulic cylinders interconnected across the road in such a way that their top sections are joined by a common platform which enables them to deform equally as a vehicle presses above the platform and retract due to spring forces as the tyre leaves the bump. As the platform moves up and down, vacuum is formed in the tank thereby causing oil to be sucked from the oil tank and pumped into hydraulic accumulators. Check valves have been installed at the inlet and outlet of each cylinder to allow hydraulic oil flow from the suction line to the pumping line without interfering the pumped oil to a wrong direction (Fig. 6). The accumulators store the hydraulic fluid at a pre-set pressure and then release it to drive the hydraulic motor which performs mechanical work. Stroke (travel distance) of the pressing cylinders equals the maximum allowable height of the road bump in a particular city. To make trafic flow possible, the platform of the proposed energy generating speed bump system will be concealed under the road with only a small portion protruding out to catch up vehicle weights while the hydraulic tank with accumulators, valves and hydraulic motor which is the power take-off point will be remotely located (preferrably beside the bus stop) to drive mechanical systems such as electric generator shafts.

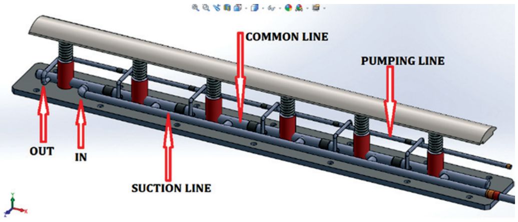


Figure 6: The deformable speed bump showing hydraulic oil flow paths

Energy Conversion Cycle and Analyses

As a vehicle passes over the proposed speed bump platform, the vehicle weight distributed over its tyres will be imposed on it. The platform will deform under this weight. As soon as the front tyres leave the platform, springs will push the platform upward thereby creating vacuum at the suction ports of the cylinders. The successive middle (for articulated buses) and rear tyres will pump the confined oil to the accumulators where the oil is kept under pressure before being allowed to drive the power take-off. The cycle continues in turn where every single pressing of the platform will either cause oil suction from the tank or pumping action to the accumulators. After delivering its energy, the oil from the hydraulic motor circulates back to the tank for storage.

The experimental set up given in Figure 5 is capable of testing loads equivalent to those of a small car up to that of a light truck of about 6 tonnes. When higher loads of about 7 tonnes were tested, the test spring on the experimental device was well compressed to its solid length which could not guarantee proper accuracy of the data for such higher values. Therefore; in order to analyse the system behaviour for load values like those of BRT buses full of passengers, a computer simulation method was employed.

Stress Analysis on the Platform

When in action the platform and its springs are subjected to high stresses and therefore analysis to determine their suitability is necessary. The platform is assumed to be under point load on two end points where the tyres press as the buses pass over while the springs are modelled based on fatigue failure mode as they are in constant cyclic stresses according to this application. Based on the data collected, the weight of a public commuter bus is 15 tonnes. Therefore, analysis conducted in this study has covered a range of weight classes from 6 tons to 18 tons ensuring that different bus weight variations are covered too. The platform made of plain carbon steel was subjected to maximum weight of 18 tonnes and simulated on a computer. The maximum stress and deflection were recorded near the end points where the tyres press on the platform and are within acceptable limits as seen in the deflection simulation view in Figure 7.

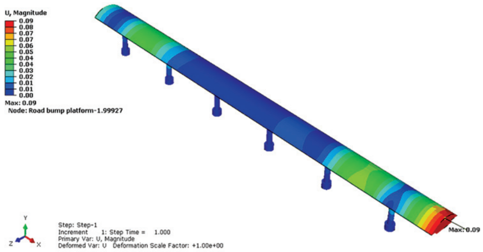


Figure 7: Simulation of the platform showing deflections when subjected to 8-ton axle load

Spring Force Analysis

Similar analysis was conducted for the compression springs under the platform as shown in Figure 8 having wire diameter of 10 mm, 7 active turns and 70 mm coil diameter. The springs are made of shot peened Silicon-Chromium (Si-Cr) alloyed steel wire with tensile strength of 2230 MPa. This type of spring tends to have appreciable fatigue strength with about 108 life cycles as tested by some researchers (Kaser *et al.,* 2011: Gariboldi *et al.,* 1994).

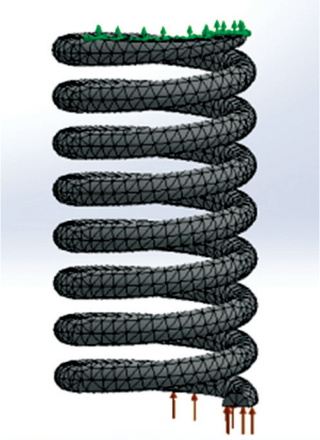


Figure 8: Compression spring showing meshing and loading points during simulation

The springs under the proposed application are subjected to frequent torsional shear stresses as the platform moves up and down under the influence of the bus weights. They were therefore, modelled based on fatigue shear stress failure mode by using Goodman fatigue criterion such that:

$$\frac{1}{N} = \frac{\tau_m}{S_{us}} + \frac{\tau_a}{S_{es}} \quad \text{...(1)}$$

Where;

N: Factor of safety

τ_m: Mean shear stress (MPa)

τ_a: Alternating shear stress (MPa)

S_us: Ultimate shear stress (MPa)

S_es: Endurance strength in shear (MPa)

The maximum and minimum bus weights considered in this study were 18 tons and 6 tons respectively. The springs were therefore subjected to fluctuating stresses that correspond to these vehicle weights.

Simulation results suggest that under normal operation, the springs are not expected to fail under fatigue loads as the values recorded for an 18-ton bus loading are still below the fatigue failure of the material (Fig. 9) while the loading to the solid length of the spring is still at relatively low value with respect to the yield strength of the spring material (Fig. 10).

Analysis on other intermediate weight values with their respective stress amplitudes

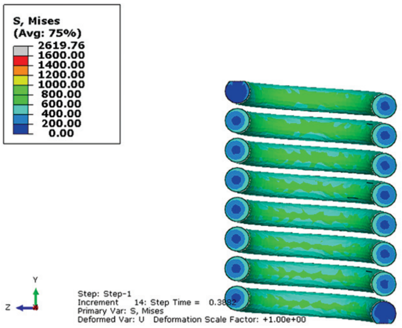


Figure 9: Simulation results showing stress values for 8-ton axle load on each spring at spring's normal operating length

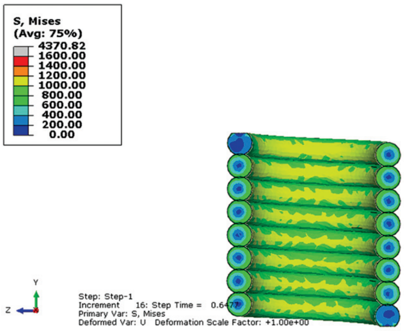


Figure 10: Simulation results showing stress values for 8-ton axle load at spring's solid length

was also carried out and presented in Table 1. These stress values are necessary as they help with calculation of the proper spring diameters and selection of spring wire material that will be suitable for the proposed application. The stress amplitudes were calculated on the basis of 7.5% preload of the minimum axle load.

Table 1: Variation of vehicle tyre's pressing force with stresses imposed on a single spring

No. of entries	Vehicle axle load (Ton)	Spring max.stress amplitude (MPa)
1	3.0	434.13
2	4.0	590.57
3	5.0	747.02
4	6.0	903.45
5	7.0	1059.90
6	8.0	1216.35

Hydraulic Accumulator Modelling

Another important component in the energy analysis of this system is the hydraulic accumulator. The device is used in hydraulic systems to store hydraulic fluid at a predetermined pressure value before releasing it to the system to provide power back up or improve hydraulic system performance by maintaining constant system pressure, absorbing pressure ripples or increasing fluid flow rate. The proposed deformable speed bump system is fitted with two nitrogen gas filled bladder-type hydraulic accumulators each having a capacity of 50 litres. Typical maximum operating pressures for such accumulators are around 300 Bar with high flow rates of 750-900 litres/min. For the sake of this study, the analysis was made based on the hydraulic motor capacity which is the power take-off in this work. The proposed motor has a displacement of 70 cubic centimetre / revolution set to run at 1800 rpm.

The flow rate of a hydraulic motor is calculated by using this fluid power formula:

$$Q = \frac{V_{g \times n \times \eta_v}}{10^2} \quad \text{..(2)}$$

Where;

Q: Flow rate in litres per minute (l/min)
V_g: Motor displacement (cc/rev)
n: Rotational speed of hydraulic motor (rpm)
η_v: Volumetric efficiency of the motor (given as 0.90)

From Eq. (2), the motor which is set at a maximum operating pressure of 200 Bar should theoretically provide a flow rate of 113, 4 litres /min.

Considering the nature of the proposed deformable road bump, the accumulators should be filled with the hydraulic oil by the short stroke cylinders whenever the platform is pressed as a vehicle passes over, until they are full and at a set operating pressure. The oil will only start flowing into the accumulator if the pressure imposed on the platform exceeds the pre-charge pressure set in the accumulator bladder. This means hydraulic oil is filled into the devices only intermittently, which makes the filling process gradual with negligible temperature difference (isothermal process). However; the discharging process is fast and continuous (adiabatic process) as the nitrogen gas inside the bladder expands and ejects the pressurised oil to drive the hydraulic motor. It is for this reason that the accumulator is modelled in two steps, gradual filling process and fast discharging. The gradual filling process is governed by this equation:

$$V_0 = \frac{Vw}{\left(\frac{P_0}{P_1}\right) - \left(\frac{P_0}{P_2}\right)} \text{......................................(3)}$$

Where;

V_0 : Accumulator capacity (gas volume) (litres)

Vw: Usable hydraulic oil from the accumulator which is the difference between maximum and minimum operating gas volumes (litres)

P_0 : Gas pre-charge pressure (bar)

P_1 : Accumulator’s minimum operating pressure (bar)

P_2 : Accumulator’s maximum operating pressure (bar)

As for the oil discharging, the equation includes a polytropic constant n (n=1.4 for nitrogen gas) in order to account for the temperature variation. The equation is now modified to:

$$V_0 = \frac{Vw}{\left(\frac{P_0}{P_1}\right)^{1/n} - \left(\frac{P_0}{P_2}\right)^{1/n}} \text{................................(4)}$$

With the accumulator volume capacity of 50 litres and the pre-charge pressure P_0 set to about 90% of the minimum operating pressure as recommended in accumulator applications, the following values of useful hydraulic oil are discharged corresponding to the assigned operating pressure values (Table 2).

Table 2: Amount of hydraulic oil discharged from accumulator per given operating pressures of nitrogen gas

Charge P_0 (bar)	Min.P_1 (bar)	MaxP_2 (bar)	Discharged oil V_w (litres)
40	45	23.80	125
45	50	25.22	150
50	55	26.28	175
55	60	27.10	200

As seen in Table 2, the usable oil volume, Vw increases with the difference between the maximum and minimum operating pressures. The energy conversion cycle can be traced through the hydraulic circuit given in Figure 11, where the cycle starts with the bus tyre pressing on the platform and causing hydraulic oil from the tank to be sucked and pumped into the accumulators. This starting point is termed as oil pressure source. Inside the accumulators, oil is kept under pressure and is prevented from flowing out without intentional action by using a check valve. When the accumulators are full of oil and the maximum operating pressure P_2 is reached, the pressure sensor Prs1 sends information to the pressure switch Prs1 of the electric system which trips to close the electric circuit, energising the relay coil CR1 which energises contact CR1. From there the solenoid named “start” is energised to allow the oil discharge from the accumulators through the solenoid actuated directional control valve, DCV to the hydraulic motor where the pressure energy of the hydraulic oil is converted into mechanical energy by running the electric generator mounted with the motor shaft. To protect the system against pressure, build up when the accumulators are full and no discharge of oil is allowed (i.e. vehicles continue passing over the platform), a pressure relief valve PRV is included which directs any surplus oil into the tank. As soon as the operating pressure falls to P_1, the pressure switch shifts again, cutting the electric signal which de-energizes the solenoid and closes the DCV which blocks the oil flow until the pressure rises again. The speed of the hydraulic motor is controlled by the flow control valve at its inlet while the brake valve, BRV at its outlet, prevents the motor against over-running loads.

Simulation view of the proposed system (designed and run on Automation Studio software) is shown in Figure 12, while variation of the motor rpm with the pressure generated is shown in Figure 13.

One of the advantages of a hydraulic system is its ability to maintain constant torque at a given speed. With the operating pressures listed in Table 2, the torque generated by the hydraulic motor can be calculated by using this formula:

$$M = \frac{p \times V_g}{20 \times \pi \times \eta_{hm}} \quad \text{.......................................}(5)$$

Where;

M : Torque generated by the motor (N.m)

p : Hydraulic fluid pressure (bar)

V_g : Motor displacement (cm^3/rev)

ηhm: Hydro-mechanical efficiency

Results and Discussion

This study introduces deformable speed bumps as alternative means of generating energy from weights of vehicles and their application with the Dar es Salaam Bus Rapid (UDART) Transit system. It is aimed that the energy so

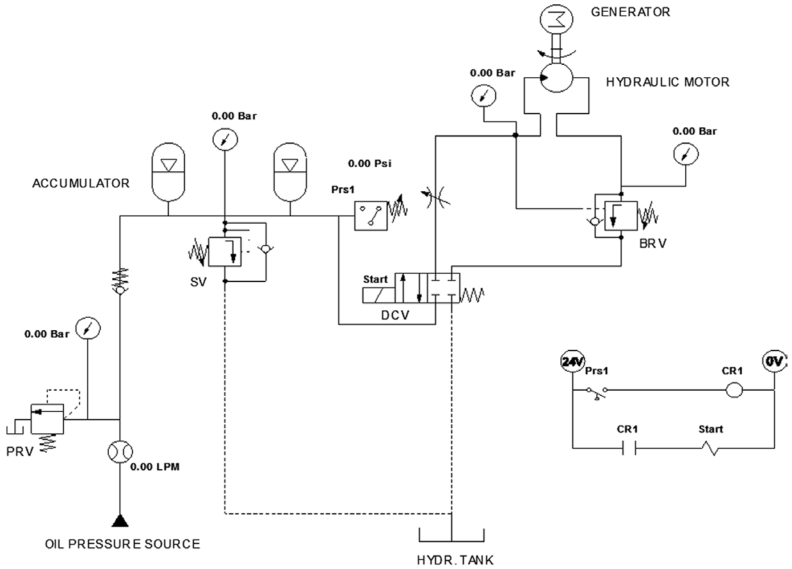


Figure 11: Hydraulic circuit with its electric control circuit of the proposed speed bump system

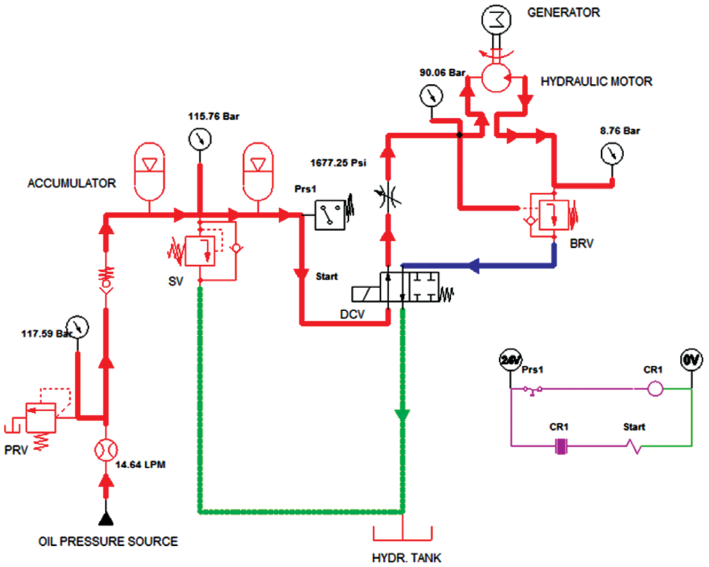
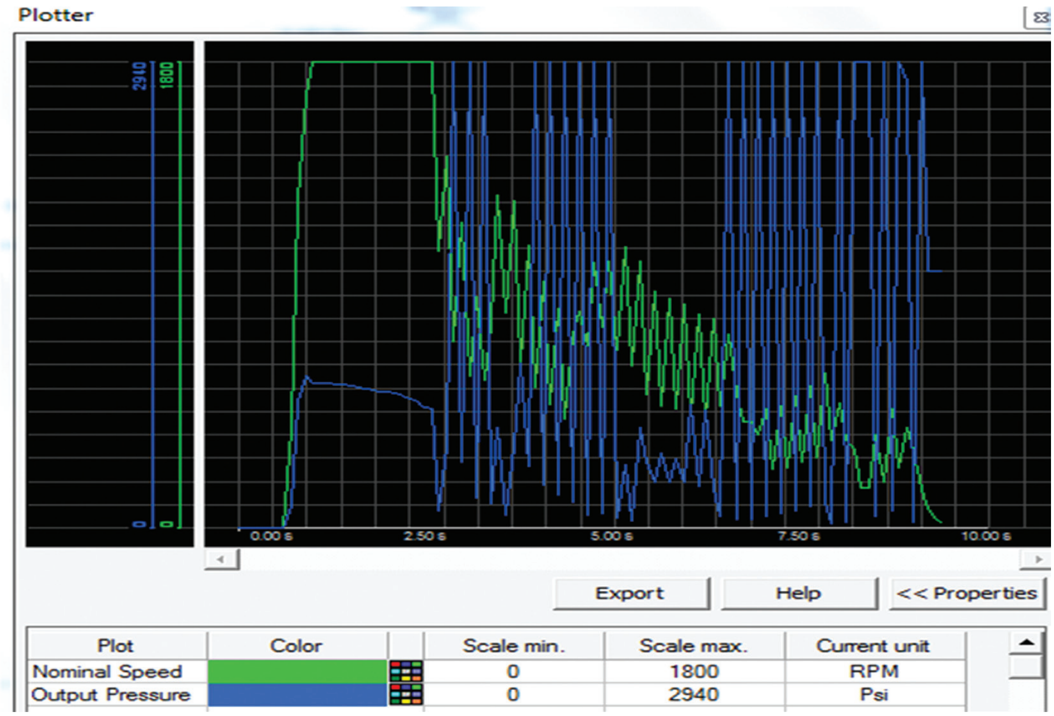


Figure 12: Simulation view of the actuated circuit for the proposed speed bump system



Plot	Color		Scale min.	Scale max.	Current unit
Nominal Speed	🟩	▦	0	1800	RPM
Output Pressure	🟦	▦	0	2940	Psi

Figure 13: Simulation plotter showing variation of the motor rpm with output pressure

generated, will be used for various applications including illuminating and ventilating the passengers waiting booths. It was found that vehicles with heavier axle weights like UDART buses in peak hours yield the best performance as they induce higher hydraulic pressures in the hydraulic accumulators. On top of that the speeds at which vehicles pass over the proposed speed bump system is to be relatively low about 20 km/h to allow perfect compression of the springs in the system and this makes the commuter bus stops ideal locations of the proposed system. Depending on the required operating pressures, each of the two accumulators proposed in this system of deformable speed bump can discharge between 20 to 30 litres of hydraulic oil.

Conclusion and Recommendation

This study has shown that fluid power system can be used effectively in converting weights of vehicles into useful mechanical energy through a deformable speed bump. It has further indicated that, due to their large weights, BRT buses and of course, other heavy-duty vehicles can exert substantial pressure into the hydraulic accumulators necessary for producing much power at the system output. However, the major drawback of the system is the filling of the accumulators up to the operating volumes of oil as the filling is intermittent and the filling cylinders under the platform are restricted to 10 cm stroke (the allowable speed bump height). Calculations show that it takes between 25 to 50 pressing cycles to fill up the accumulators to the working volume. That means, about 12 to 25 two-axle buses need to pass over the platform to achieve the intended volume of oil. The system can also be installed at the entrances and exits of the bus depots where all the buses pull in for maintenances and stopover. Therefore, the study recommends inclusion of more three-axle buses in UDART fleet in order to favour the proposed system in terms of filling up the accumulators in a short time as with such buses, three pressing passes of the platform will be achieved instead of just two found on the current two-axle buses. We also recommend that, the second and third phase of the Dar es Salaam BRT system should provide more bus fleet to ease mass transportation, involve extension and restructuring of the infrastructure to include establishment of the energy generating deformable speed bump systems proposed in this study.

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