

Modeling and Simulation of Heavy Vehicles' Air Brakes: Applicable Laws of Physics

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ABSTRACT

Performance and failure of heavy vehicles' air brakes using computer models is a subject of high interest in the area of accident reconstruction. The performance of heavy vehicle air brakes depends on several Pneumatic-Mechanical systems with many components working together. Bond graph modeling technology is appropriate for this multi domain application where pneumatic and mechanical components must work simultaneously. Bond graph models allow an automated modeling generation approach. They produce first order equations in state space form suitable for simulations in the time and frequency domain. Due to the high order of the system composed of many components, conventional methods based on the constitutive laws of each element become complex very quickly and prompt to errors. The bond graph modeling technique implemented in the software CAMPG (Computer Aided Modeling Program with Graphical Input) generates computer models ready for simulation in MATLAB. The paper examines heavy vehicle air brake system models of components and of the whole system. It presents the physics principles that apply to generate the braking forces. The relation between simulation and air brake sizing variables is considered in time dependent operating conditions. The paper presents also a practical application of a three axle ten wheel heavy vehicle. It explains the physics principles that apply for a heavy vehicle braking under downhill failure conditions.

Keywords: Heavy vehicle air brakes, accident reconstruction, air brake failure, drum brakes, downhill braking, work-energy dissipation, braking forces.

1. INTRODUCTION

Using basic constitutive laws for mechanical and pneumatic systems one can generate computer simulation models. The laws of Physics control the motion of heavy vehicle dynamics as presented in references Beer and Johnson (2004), Jazar (2000), Fricke (2010). Design considerations and equations that control the motion of vehicle are presented in Jazar (2000) and Granda (2019).

Heavy vehicles' air brakes have several modes of operation. The term "Service Brake" is used to indicate the operation of the brakes under air

pressure and normal movement of the vehicle. The term "Parking brake" or "Spring-parking brake" describe the brakes that operate on the same shoes and drums of the service brakes but they are strictly mechanically activated. . These are also known as Emergency Brakes. Powerful springs act on the push rods that activate the brake shoes to generate the braking forces. Their operation does not depend on maintaining the 110 lb. air pressure required for normal operation of service brakes. If a loss of pressure below 60 psi occurs on the service brakes pneumatic circuit, by design, the spring-parking brakes are triggered and activated immediately. Another term used in this paper is "working brake". This term refers to a condition of maintaining the vehicle stopped while the hydraulics on the back perform several tasks, typical operations of specialized trucks. In order to achieve this, the

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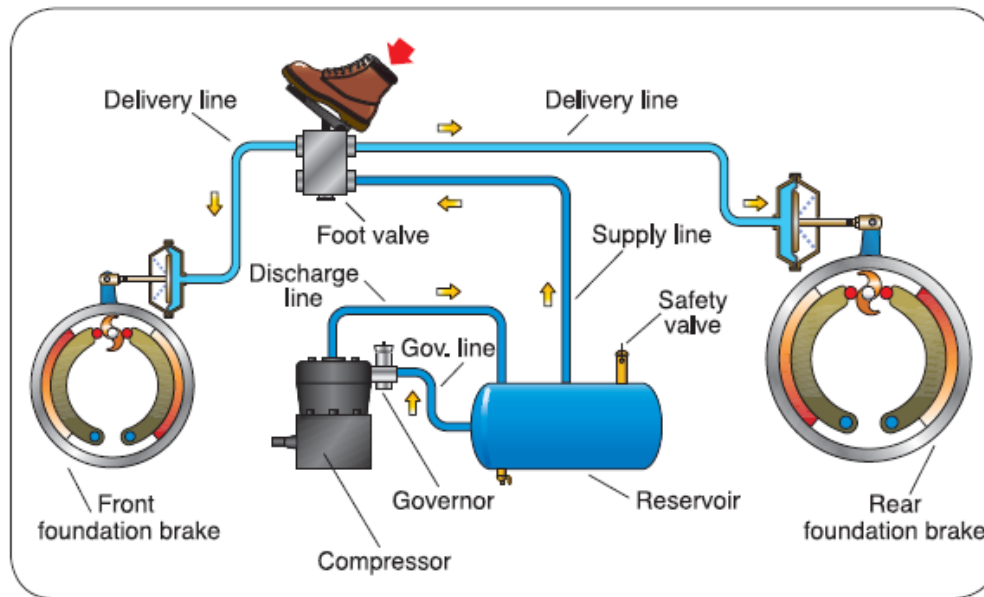


Fig. 1 Basic braking components of a heavy vehicle. Yukon (2014)

operator places the transmission in neutral, allowing speeding up of the engine and operation of the hydraulic mechanisms for specific applications. This system triggers the service brakes to apply to all wheels, keeping the truck from moving.

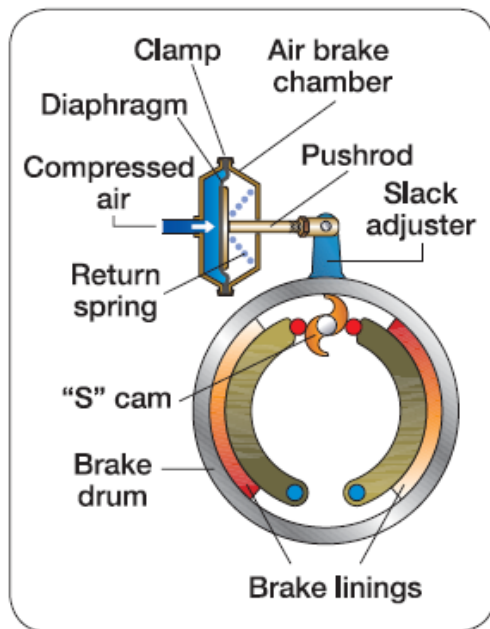
A loaded Recycling Truck on a hill is presented as an application of downhill brake failure. It is tested under a partial loss of pressure. An air pressure loss diminishes the brake forces because these control internal friction forces at the drums level. In this example, despite the fact the spring-parking brakes are designed to apply automatically, in case the pressure drops below 60 psi and failed to apply. They did not trigger to lock the back wheels acting as an emergency brake. Despite the truck rolling 131 ft. and descending 15 ft. downhill on an 8.5% hill and on a subsequent 19% section, it stopped a few feet from a house at the bottom of the hill. Why did it stop after it rolled down becomes a major question? The laws of physics and computer simulation models are used to research the answer. The laws of physics for conservation of energy, work-energy, and energy dissipation and brake forces applied at the wheels provide the scientific foundation.

2. HEAVY VEHICLE AIR BRAKE SYSTEMS OPERATION

2.1. Basic Components

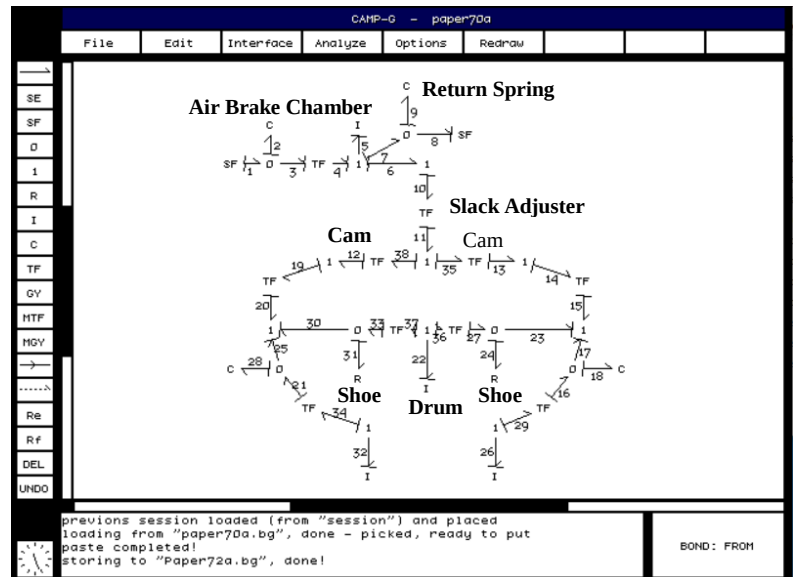
In Fig. 1 a diagram of a basic heavy vehicle braking system is presented based on the description in Yukon (2014). One can also consider the diagrams presented in Fricke (2010). Using these basic system bond graph models are developed with an incremental level of difficulty from a system at one individual wheel until a complete integrated vehicle brake system is developed.

In Fig 1, a compressor pumps air into the Reservoir, the Governor controls the pressure that compressor produces. The blue air lines allow air flow between components for the front and back brakes. A Reservoir stores the compressed air. The brake pedal is known as the foot valve, it controls the flow or compressed air to the components in the front brakes and the in the back brakes. Fig. 2 (a) illustrates the basic components Yukon (2014) and Fig. 2 (b) the corresponding bond graph.



(a)

Fig. 2 (a) Single wheel brake components



(b)

(b) CAMPG Bond Graph Single Wheel brake components

Pressure is received from the air flow to the Air Brake Chamber. The air pressure in the chamber is converted in mechanical force through the push rod. The pressure acts on a flat circular plate in the chamber that is attached to a diaphragm. The push rod pushes the slack adjuster (blue) and makes it rotate clockwise. That slack adjuster is connected to a camshaft and this to an S cam which ultimately is used to expand the shoes against the rotating drums in order to produce the braking forces.

In this case we have a Type 30 clamp chamber with 30 square inches of effective diaphragm area. If 100 psi is applied, it develops a push rod force which we calculate multiplying the pressure times the effective area so $100 \text{ psi} \times 30 \text{ in} = 3000 \text{ pounds}$.

2.2 Brakes Applied and Released

Fig. 3 illustrates the flow of air when the brakes are applied. Fig. 4 illustrates the flow of air when the entire pressure is released in the foot valve, Yukon (2014). Front and back brakes are released. This status is the state of the brakes for normal driving conditions.

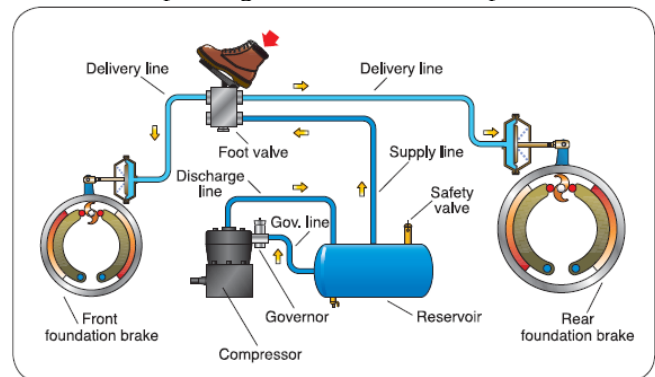


Fig 3 Brakes applied

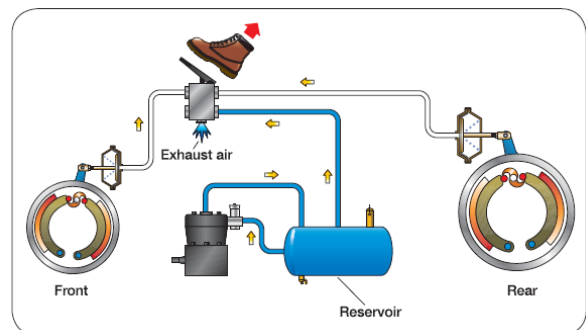


Fig 4. Brakes Released

In Fig. 4 when the foot valve is released, air is released from the valve to the outside from the line causing the braking forces to disappear as the pressure goes down. Note that the slack adjusters

are relaxed and the go back to a position less than 90 degrees. The brake chambers have now no pressure on them as the air is released from the foot valve exhaust.

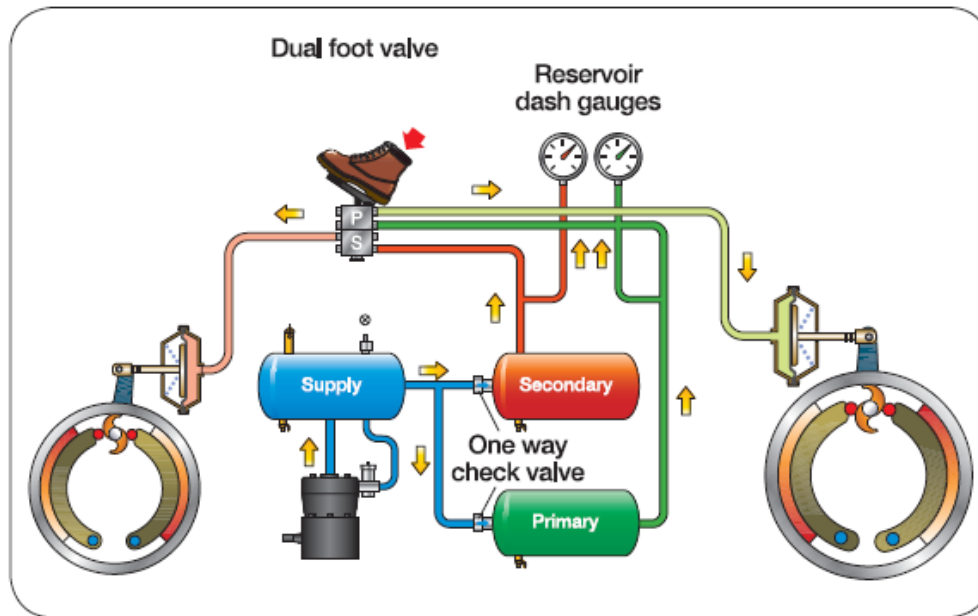


Fig. 5 Dual Air Brake System

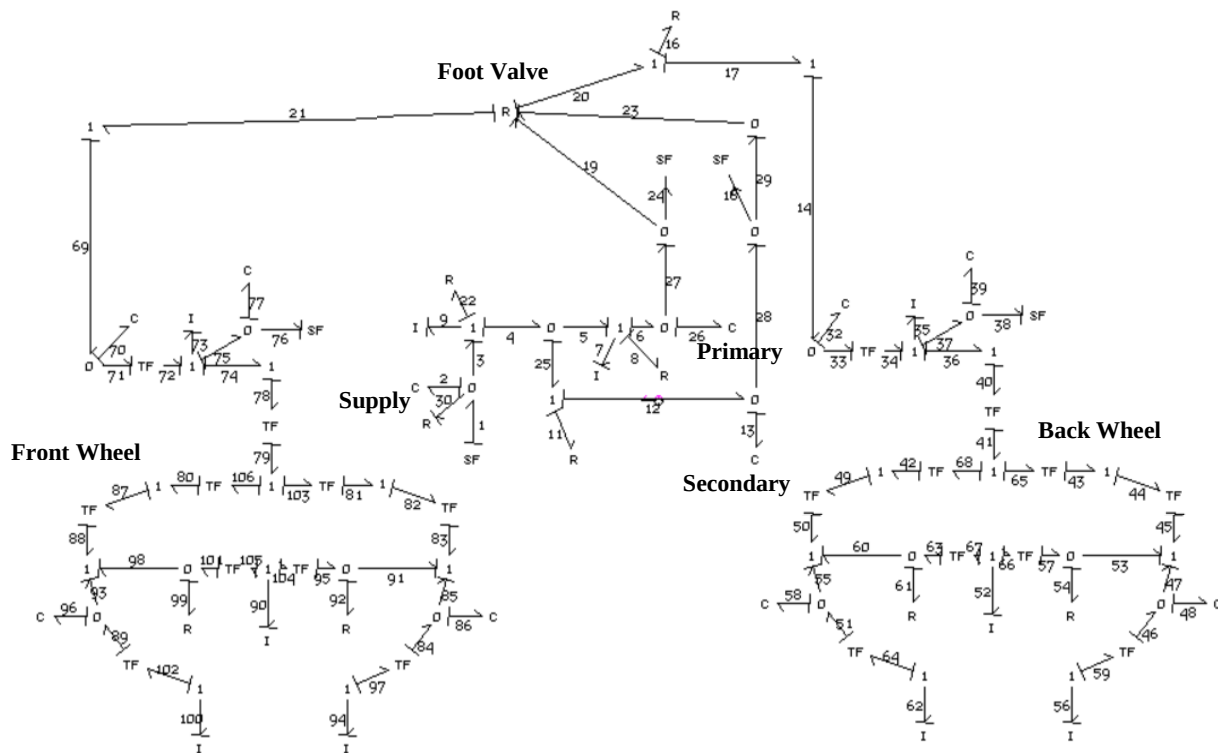


Fig. 6 Dual Air Brake System Bond Graph produced in CAMPG

2.3 Dual Air brake system plus Spring-parking brake

Trucks have a dual braking system as described in Fig 5. This means they have a dual foot valve. The system is divided in two systems, each having its own supply, delivery and exhaust ports. This valve controls two air circuits, one for the back (primary,

green) and one for the front (secondary, red). When a driver presses the foot valve, both sections are activated, primary tank to rear axles, secondary tank to the front. There are two pressure gages one for each service tank. The idea is that even if one the systems fail completely, the driver would have some brakes, maybe not full power, but will be able to control the vehicle to a stop.

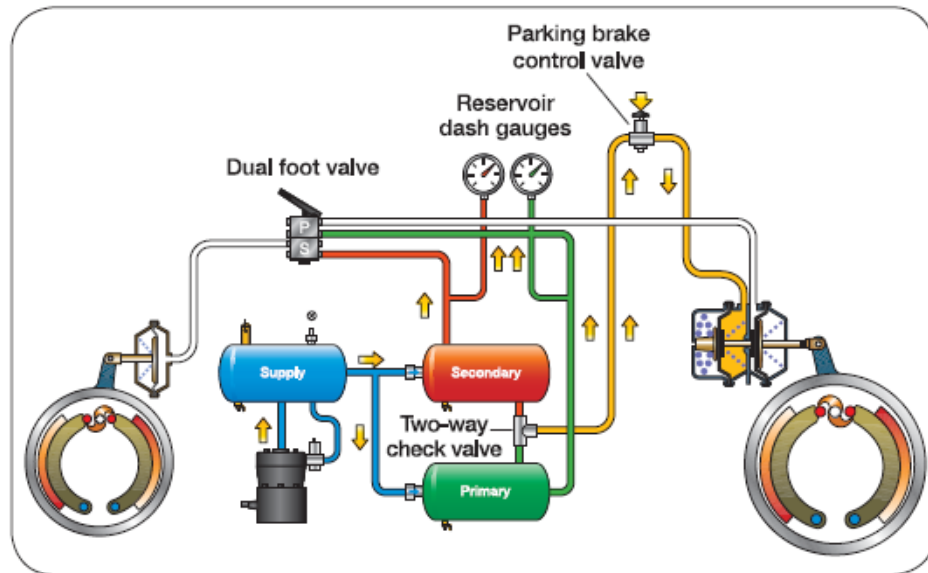


Fig 7. Complete System. Dual air brakes plus Spring-Parking brakes. Yukon (2014)

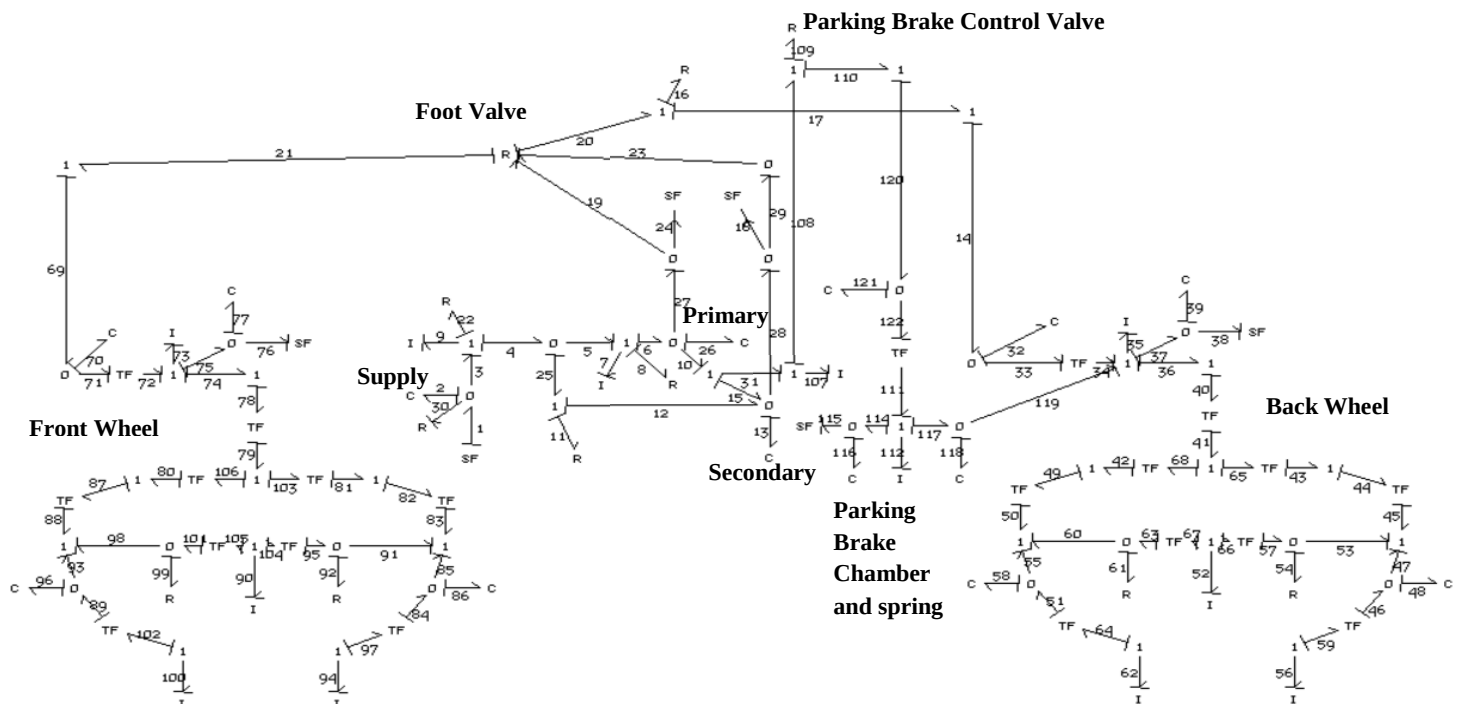


Fig. 8 Complete System. Dual air brakes plus Spring-Parking brakes bond graph produced in CAMPG

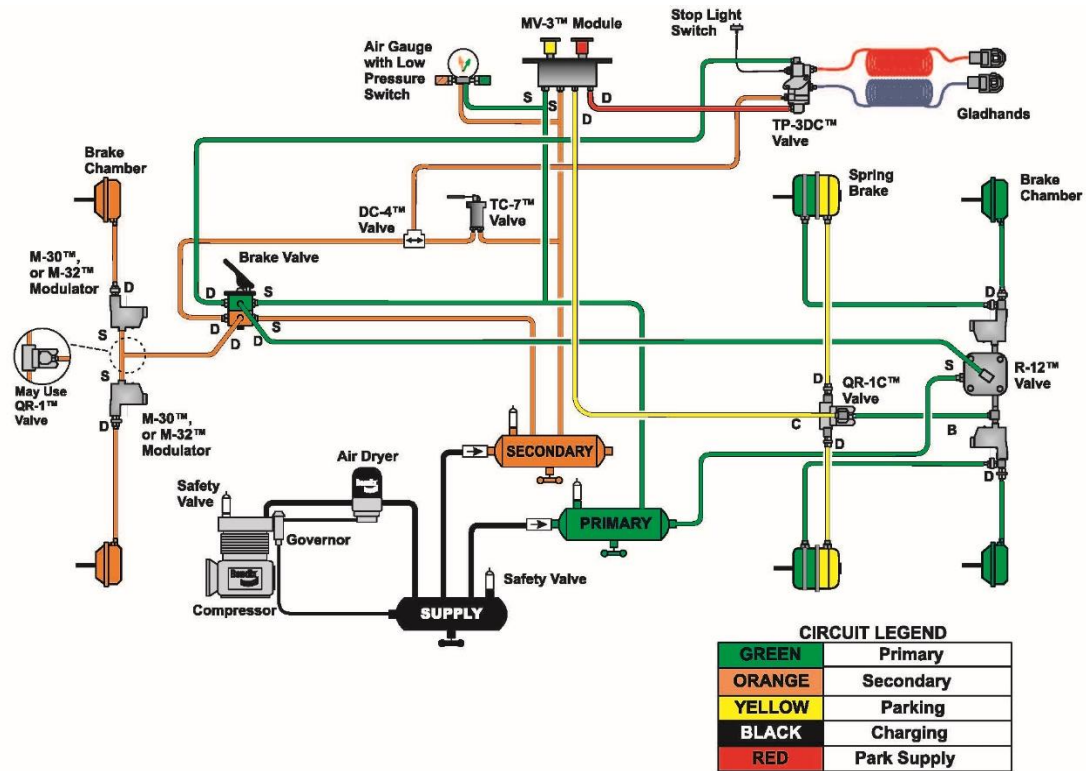


Fig 9. Ten wheel heavy vehicle air brake system. Bendix commercial Vehicle Systems (2004)

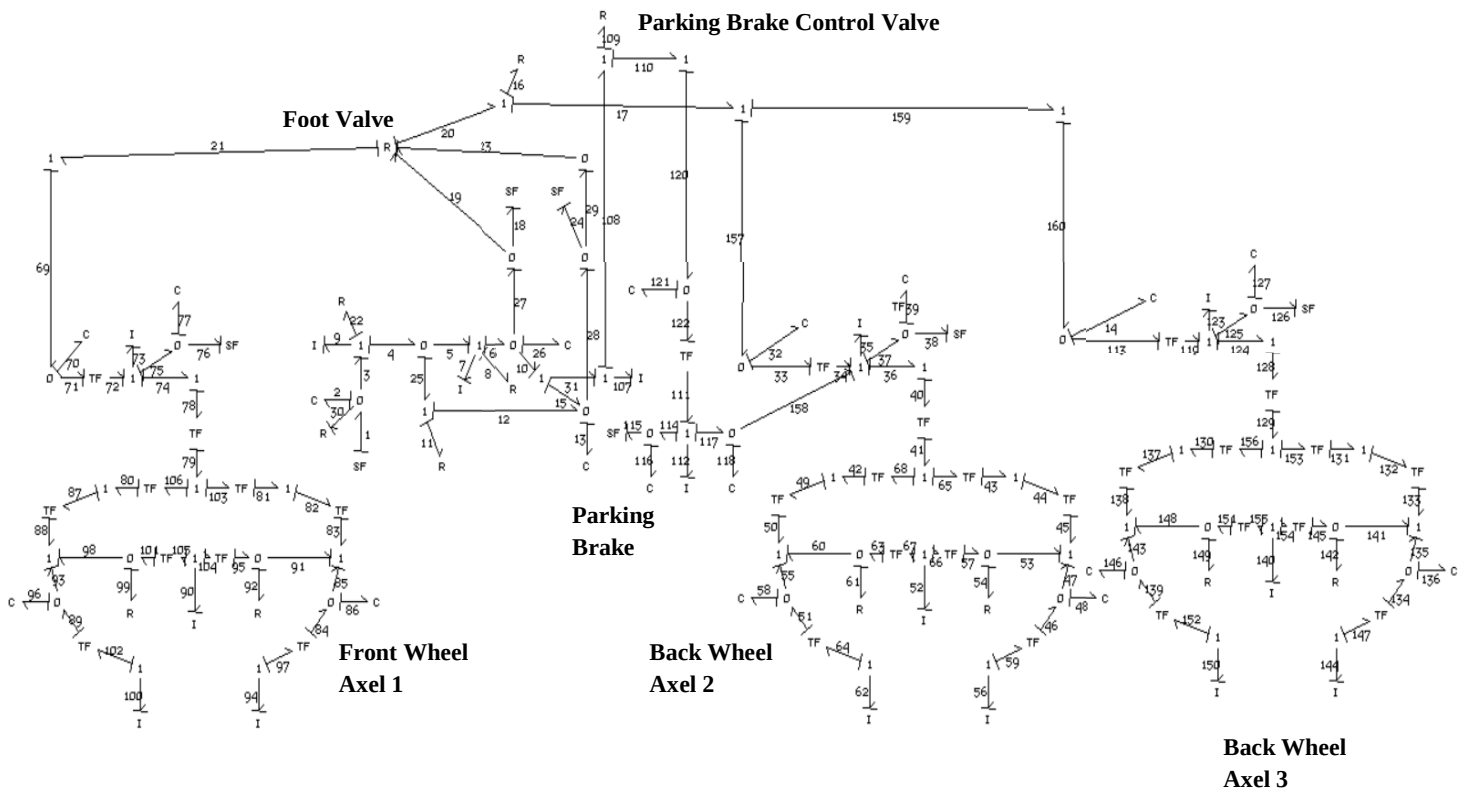


Fig 10. Heavy vehicle with three axles air brake system bond graph model produced with CAMPG

The Spring-parking brake circuit is shown in the yellow circuit of Fig 8 and Fig 9. The yellow circuit is pressurized. If the operator pulls the knob up, the air pressure is released from the brake chambers and only the mechanical springs are activated. Their forces act on the push rods and apply the brakes to axles 2 and 3. This is enough to stop a heavy vehicle on an incline. In Fig 10 shows the bond graph model expanded to a 10 wheel vehicle.

3.0 HEAVY TRUCK DOWNHILL BRAKE FAILURE APPLICATION

A Recycle truck was on an 8.5% inclined stopped at the top of the hill. Its personnel collecting recycling material cans and compacting the recycling material on the back while the vehicle was stopped under the control of the “working brake”. It is set by the driver with a button that disables the pedals and sends the air pressure to the service brake lines. This keeps all wheels from moving while the hydraulics on the back are used. It sets the transmission in neutral, speeds up the engine and allowed the hydraulic systems and compactor to operate. Under these circumstances the pressure to all wheels is as if one applied the service brake. Thus an application of air pressure to the brake chambers on all wheels keeps the truck in place. The engine would speed up to operate the recycling material compactor, sweeper etc. At that point the working brake controlled the truck.

The truck remained stopped on the hill for several minutes while the workers were collecting recycling material homes on both sides of the street. All of a sudden there was an unusual loud hissing

sound emitted from the truck and then the truck started to roll slowly downhill towards the front yard of the home at the bottom of the hill approximately 88 feet away. The truck left the asphalt and its wheels kept on rolling over the curb and into the inclined front yard of a property for another 29 feet. Its wheels rolled on the inclined front yard which has an inclination of approximately 20%. The truck finally descended into the home front cement patio, travelled 14 ft. and stopped approximately two feet from the entrance to the home. By the time it stopped, it had descended about 15 ft. from the height at location where it started rolling and had dissipated approximately one million joules of energy. The scientific questions. Brakes failure? If so, why after failure and roll downhill descending 15 feet it stopped?

3.1. Overall Scenario

The recycle truck shown in Fig 11 had potential energy with respect to the flat ground level where it stopped. For purposes of our analysis the bottom, the patio is the reference plane at height zero. The kinetic energy is zero at the top of the hill because the truck was stopped motionless on the hill. Fig 11. shows a cross section of the terrain with the corresponding dimensions and slopes which determines the height the truck descended from the top. The 8.5% slope corresponds to an angle of 5° . The 19.6% slope on the grassy area corresponds to an angle of 11° . The truck rolled on the pavement approximately 88 feet. It rolled on the grassy area 29 feet and its center of mass travelled 14 feet on the cemented patio.

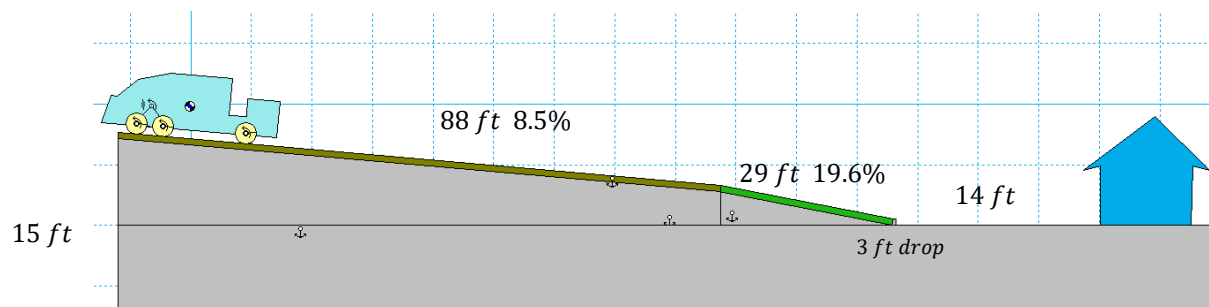


Fig. 11 Overall truck path due to brake failure.

3.2 THE LAWS OF PHYSICS THAT APPLY ON THE DOWNHILL ROLL

3.2.1 Potential and Kinetic Energy

Potential Energy:

$$PE = \text{weight } (w) \times \text{height } (h) = w \times h \text{ [ft-lb]}. \quad (1)$$

This product of force times a distance is also known as “work”. When objects move they also acquire energy and this energy is measured by the kinetic energy:

$$\text{Kinetic Energy} = KE = \frac{1}{2} m v^2 \text{ [ft-lb]} \quad (2)$$

Where m = mass of the body

$$v^2 = \text{square of the velocity} \left[\frac{\text{ft}^2}{\text{sec}^2} \right]$$

The truck’s potential energy transformed into kinetic energy and work of friction. Several possibilities were studied. During the free rolling test, the truck acquired a velocity of 17.46 miles per hour before it went into the patio. There were no friction forces to dissipate the energy, then energy is conserved. Therefore the truck would not have stopped and crashed into the house at the bottom.

3.2.2 Conservation of Energy

In free rolling, the Principle of Conservation of Energy applies, Beer and Johnston (2004)

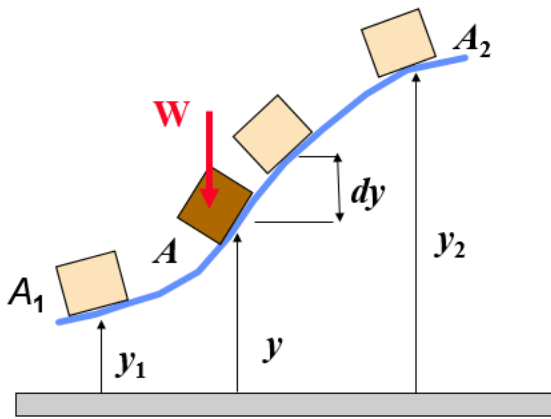


Fig 12. Work of a conservative force is equal to the change in potential energy.

$$U_{1 \rightarrow 2} = - \int_{y_1}^{y_2} W dy = W y_1 - W y_2 \quad (3)$$

Where U is the work done, W is the weight, y is the height $W \times y$ is the potential energy. Therefore, we read the work done by the weight W from moving from height y_1 to y_2 is equal to the change in Potential Energy.

The sum of the potential energy plus kinetic energy at position 1 of an object have to be equal to the sum of the potential plus kinetic energy at position 2.

$$T_1 + V_1 = T_2 + V_2 \quad (4)$$

T_1 at the initial position on the hill is = 0 because no velocity, V at the bottom of the hill (patio) is 0 because the patio is our reference 0 for the height. In free roll the potential energy the truck had at the initial position on the hill is transformed into kinetic energy at the bottom because it acquires a velocity. Because the truck descended and stopped leads us to the conclusion that energy was not conserved but it was dissipated. The only explanation lays on the some braking forces still acting. The initial potential energy transformed in work of friction is the explanation as to why it stopped on the patio and did not hit the house.

Based on these Laws of Physics, it means that if partial braking occurred, then the original potential energy at the top of the hill is equal to the kinetic energy plus the work done by the braking forces at any point between the top of the hill and the bottom. When the truck stopped at the bottom, its kinetic energy is zero but then all the potential energy had been dissipated into work of friction by the braking forces, thus fulfilling the Principle of Conservation of energy. Granda (2019) presented applications of this principle to accident reconstruction.

The measure of the energy dissipated, is calculated by the work of the friction forces. Initial energy weight 44,420 lb. times the vertical distance it descended (15 ft.). This number is 666,300 ft-lb or 905,821 joules. This energy had to be dissipated so that the velocity would be zero at the patio level. Where did this energy go? The scientific answer is that, despite the fact there was a loss of pressure on the brake system, it still kept 55 psi so there was some partial braking forces acting all the way down. These combined with opposing forces when the truck hit a telephone pole, unrooted a tree, dragged it underneath and cracked a retaining

barrier contributed to dissipate the 905,821 joules of energy from the top of the hill to the patio..

3.2.3 Forces acting on the truck as it is stopped at the top of the hill

Considering the truck was on 8.5% incline, the downward component of the weight calculated is $(44,420 \text{ lb.}) \times \sin(5^\circ) = 3871 \text{ lb.}$ pushing the truck downhill. Under this force, it would acquire an acceleration unless counteracted by friction forces acting on the tires in the opposite direction. The truck holds in place on the hill with the brakes applied. The downhill force is counteracted by friction forces between the tires and the ground acting on the truck in the opposite direction.

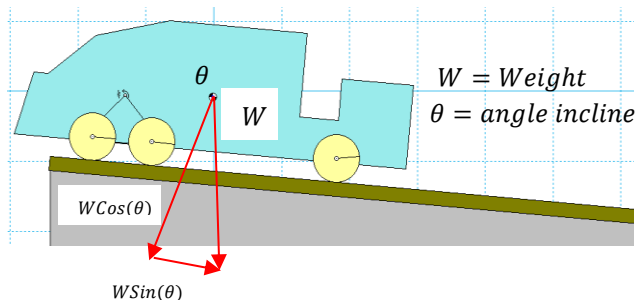


Fig. 13 Forces acting on the truck free to roll.

The friction forces originate inside the brake drums as the air brake system sustains a normal operating pressure between 100 to 120 psi (pounds per square inch) in the tanks and applies 30 psi to the air pressure lines system. Once this pressure is applied, a lever-cam mechanism pushes the brake shoes against the drums on each wheel and such friction force between the shoes and the drum produce a counteracting moment that results in the friction forces pushing uphill to hold the truck in place or to provide partial braking forces while rolling downhill. Low air pressure then produces lower braking forces. If those lower braking forces in the drums not produce enough friction forces to counteract the component of the weight acting downhill, the truck will start rolling downhill.

4.0 COMPUTER MODELS

The computer models used here considered the braking system as a whole with the purpose of examining the lowest pressure possible to dissipate one million joules of energy and still stop on the

patio before the house. There is another important consideration, the parking brake. The parking brakes are supposed to be activated if the pressure drops below 60 psi. In this case they did not.

There were many computer simulations done using vehicle dynamics principles Jazar (2000), CAMPG (2021), Working Model (2021). The objective, to verify the simulation and match physical evidence. Computer simulations verified that 905,821 joules of energy were dissipated on free roll.

4.1 Dynamic Condition 1. Free downhill roll

In order to analyze this condition we must let all wheels rotate free under the only external force that causes motion. The downhill component of the weight is 3871 lb. Fig. 13 indicates the forces acting on the truck at time =0 and all wheels free.

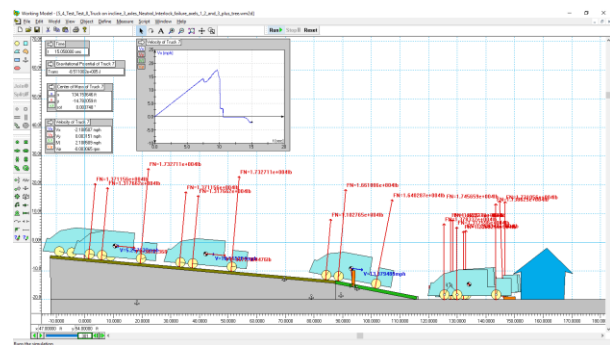


Fig. 14 Free downhill roll strikes the house.

Fig. 14 shows the sequence under free roll from the initial position on the hill until it strikes the house and discharges about a million joules. Under this condition bushes, a small tree and going over 3 ft. retaining wall did not stop it from hitting the house.

Using computer simulations one can compare the motion of the truck on free roll with the one under the pressure loss and partial braking while under the control of the working brake. During free roll, the maximum velocity is 17.46 mph. The whole event was over in 15 sec.

4.2 Dynamic Condition 2. Partial braking, downhill roll under loss of air pressure

Shown in Fig. 15 is a computer simulation of the truck rolling downhill under loss of pressure and partial braking.

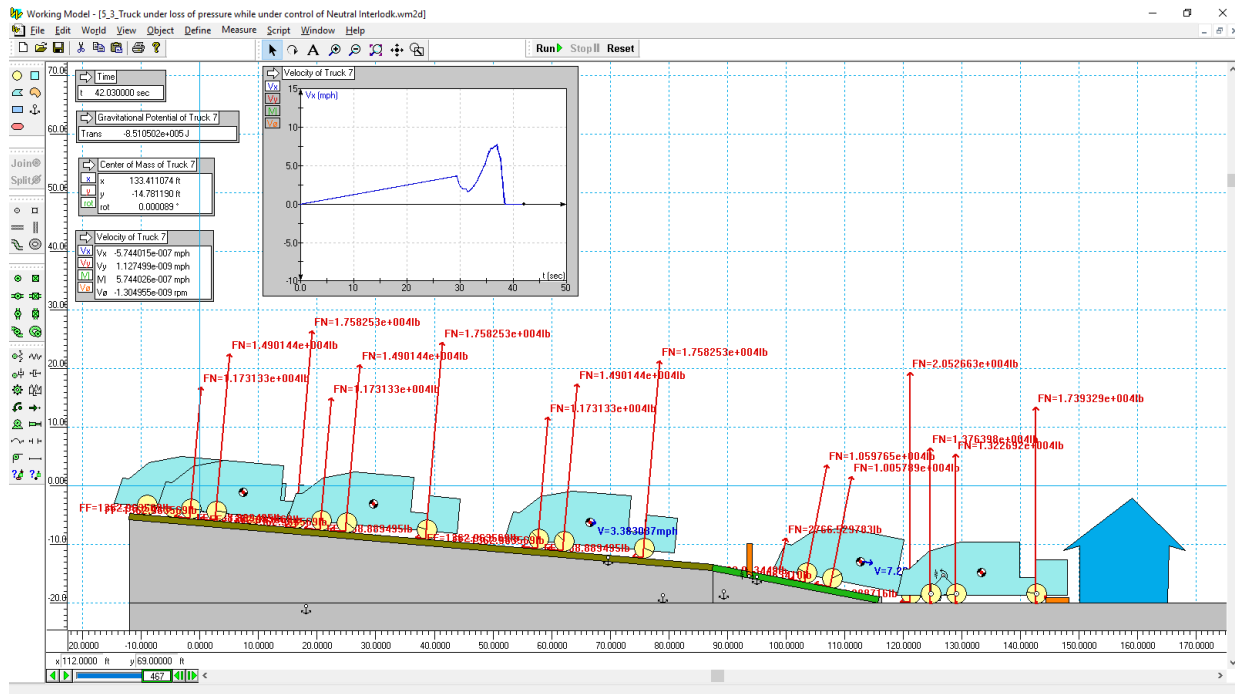


Fig 15 Truck rolling down under failure of the supply pressure while under the Working brake

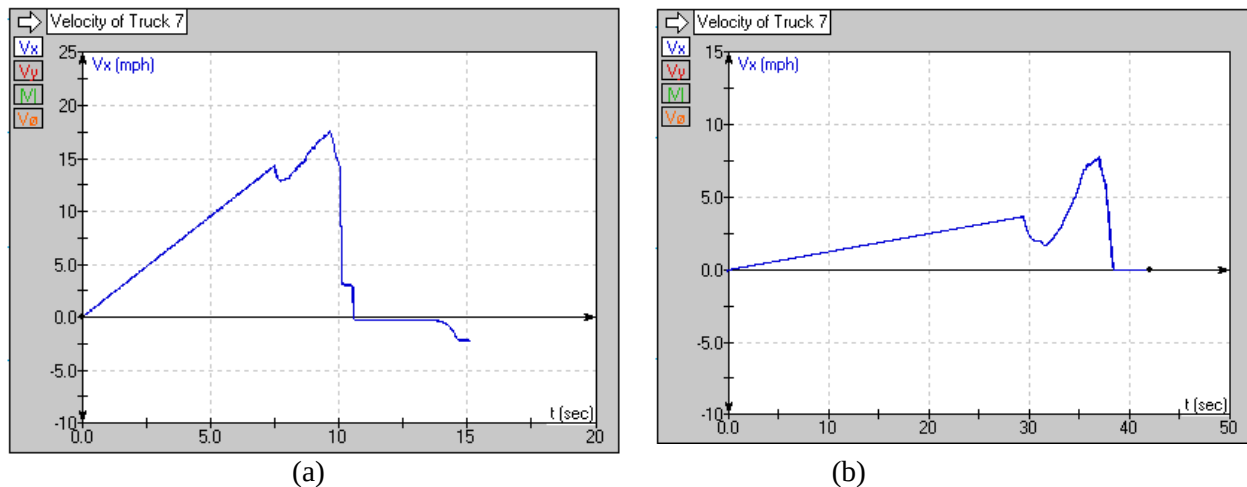


Fig 16 Truck velocity diagram a) Condition 1, free roll. b) Condition 2. Downhill roll under air pressure loss and partial braking.

The truck acquired a velocity of about 5 mph by the time it entered the front yard after rolling 88 feet. Considering this distance this is slow velocity. Because of this the driver attempted to get back into the cab but was not successful. This low speed verifies partial braking otherwise the truck would have accelerated and the speed would be higher. There was a loss of air pressure.

On Fig. 16 (a) one can see that the maximum

velocity the truck acquired was 17.46 mph and the event lasted 15 sec. Using the graph shown in Fig 16 (b) the maximum velocity under partial braking is 7.61 mph. The event lasted 38 sec. The simulation verified that under these circumstances the truck did stop and did not hit the house. It dissipated all the energy it had at the top of the hill. The simulations revealed that the result definitely is sensitive to the level of braking force produced on the braking drums. This in turn translates to the

level of pressure loss at the brake chambers. Granda Valdez (2018) present the scientific explanation of energy loss during braking.

4.3 Dynamic Condition 3. Parking brakes applied 4 seconds into the downhill roll

Computer simulations of the truck rolling downhill were conducted testing the possibility of setting the parking brake while rolling downhill had started. The idea here is to investigate whether the driver would have been able to get back in the cab and pull the knob to set the parking brake which is also called emergency brake. Intentionally, the spring-parking brakes were triggered after the truck had rolled for 4 sec and the truck had acquired a velocity of 7.5 mph.

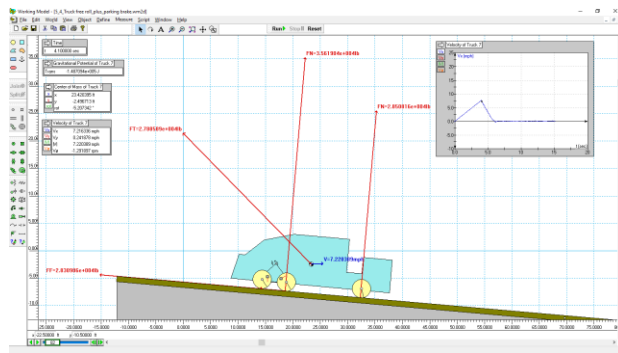


Fig 17. Application of the spring-parking brake while in motion

The result is that if the spring-parking brakes would have been applied under those conditions the truck would have stopped. This is as if the driver would have pulled the knob up 4 sec into the free roll while the truck was already at 7.55 mph. This simulates the as if the “Working brake” system would have applied the spring-parking brakes under a fault condition.

The simulation locks up the back wheels as if the parking brake is applied, a friction force of 28,309 lb. is generated to stop the truck. Then the suspension and the entire truck experiences rotation about the pitch axis (perpendicular to the paper) and settles down. The forces keep changing and shifting momentarily until the truck settles down and stops in the middle of the incline as shown in Fig 18. The meter on the right which reveals the velocity of the truck reads 0 mph stopped on 8.5% incline after the parking brakes have locked the

back wheels. This verifies that if the driver would have gotten back in the cab and pulled up the yellow parking control valve, shown in Fig. 7 the truck would have stopped.

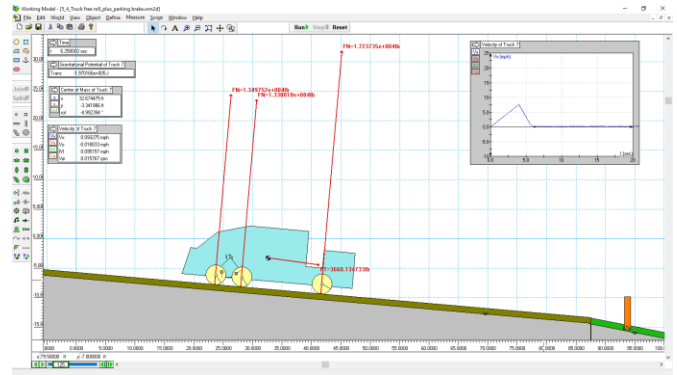


Fig. 18 Truck settles down and stops.

This simulation is very helpful for examining the design of the emergency systems a heavy vehicle should have in order to prevent a roll downhill under the loss of pressure to the chambers of the service brakes. It points out that such systems need the feedback of level sensors to tell the central control system that the truck is on an incline and any sensor that reports motion, velocity or acceleration while the truck is under the control of the working brake should be regarded as an emergency which requires the automatic application of the spring-parking brakes.

Under the conditions of partial braking the truck reached maximum of 7.61 mph. Setting of the spring-parking brakes would have stopped the truck before it reached the grass inclined front yard.

5. CONCLUSIONS

Bond graph models have been developed for the air brake system of heavy vehicles in a progressive manner, from the basic system at one drum and its components with a level of detail to the system as a whole. This demonstrates that bond graphs can produce complex models incrementally, allowing the simulation of subsystems first before moving on to more complex multi domain systems. The bond graphs presented here can be used in that manner, analyze subsystems and the entire system.

The application presented here considered the system as a whole under the downhill forces caused

by gravity. The models depicting the counteracting moments produced in the brake drums. The simulations verified that a loss of pressure produced partial braking. They verified the physical evidence on how the truck rolled downhill and how and why it stopped in front of the house.

Simulations revealed that the spring-parking brake is a key component so that the complete roll downhill could be avoided. A good design of the spring-parking brake system needs to account for back up and emergency systems triggered to act under different fault conditions. In this situation the computer model helps us examine the design defects on the working brake system for failure to include fault modes in addition to loss of power and pressure under 60 psi.

Once the working brake system was set on it was imperative to have backup systems that would have triggered the spring-parking brakes to apply considering different fault modes that would considerer: 1) Recycle trucks often work on hills such condition needs to be detected and reported to the central control system. 2) Detection of motion under operation of the working brake should trigger deployment of the spring-parking brakes. 3) Sensors to measure velocity or acceleration. Sensors that would feedback information to the control system revealing that the truck was on an incline and any motion, velocity or acceleration while the working brake system was in control of the truck is a failure mode or fault mode which should have triggered the spring-parking brakes to apply.

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