

Study of Driveline Functionality During off-road Driving of an Articulated Hauler

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Abstract

An articulated hauler is a modern construction machinery concept developed by Volvo for transport under difficult off-road conditions. The main task in development work is to optimise the behaviour and properties of the machines to this environment.

A customised version of ADAMS has been built suited for the Volvo Articulated Haulers machines. This application has a rather high level of parameterisation, which gives the user the opportunity to choose different system modules for frames, driveline, suspension and size of machine. A set of predefined drive cases, such as constant radius driving, steering angle input and path driving, can be used to drive the vehicle. The simulation environment today is not static, it is continuously developed by adding of functionality and modules to the existing application.

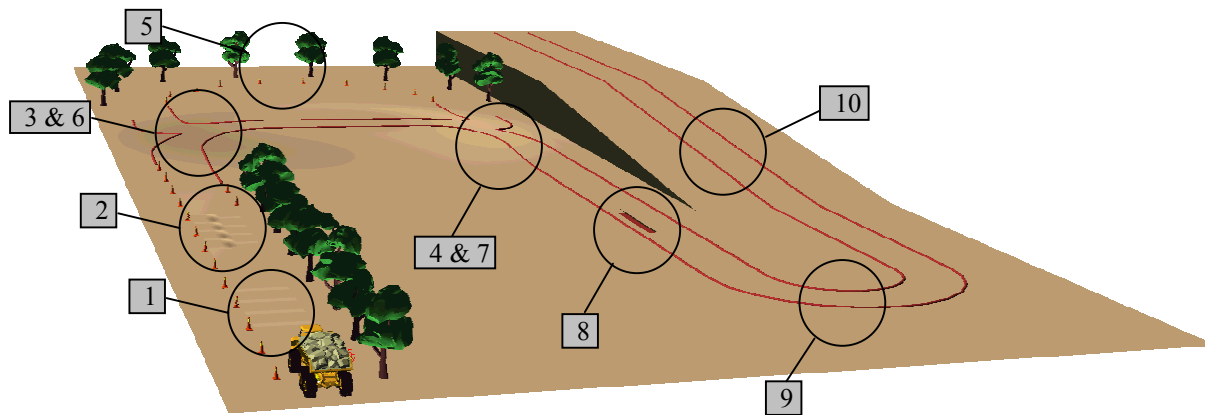
In this paper the driveline and machine behaviour is simulated in hilly conditions with varying rolling resistance, driving along a curved path. The objective is to get an understanding of the driveline functionality and to investigate the effect of locking differentials during drive. It is of interest to find a design that reduces the loads and thereby increases life of driveline components without affecting the traversability of the vehicle in a negative way. The traversability is measured in terms of wheel slip, integrated wheel slip and power delivered to ground.

Drivecase

A virtual proving ground has been built in ADAMS to allow driving the vehicle under different conditions. The vehicle runs on rigid ground with friction coefficient 0.6. No

switching of gears is allowed during driving, third gear is used in the simulation and a velocity controller keeps vehicle velocity at approximately 10 km/h. In order to follow a predefined path along the proving ground, a path controller sets the forces in the two steering actuators. Input to the path controller is the offset from the predefined path two meters in front of the front axle.

The first section of the proving ground includes washboard in phase and washboard out of phase driving, see Figure 1. No differentials are locked. Next section of the driving includes turning maneuvers right and left, uphill and downhill. The effect of locking the longitudinal differential is studied in uphill driving during turn. After turning up and down the hill, the vehicle runs straight and down in a wheel track with its right side. The wheel track is 350 mm deep and filled with mud, which subjects the vehicle to additional rolling resistance. The simulation ends with driving through a sharp U-turn with radius 10 m and then onto an inclined plane with an inclination of 10%.



- | | |
|---|--|
| 1. Washboard in phase, ampl. 150 mm | 7. Right turn, downhill |
| 2. Washboard out of phase, ampl. 150 mm | 8. Wheel track, 350 mm deep, filled with mud, increased rolling resistance |
| 3. Right turn, uphill | 9. Sharp U-turn, R=10 m |
| 4. Left turn, downhill | 10. Uphill, 10% inclination |
| 5. Long U-turn, R=25 m | |
| 6. Left turn, uphill | |

Figure 1. Virtual proving ground in ADAMS

Model description

The simulated vehicle is a fully loaded Volvo articulated hauler A40D. All parts are modeled as rigid parts except for drive shafts that have rotational stiffness. The ADAMS model contains a detailed description of the drivetrain including engine, torque converter, gearbox, dropbox, differentials, differential locks and tires. See Figure 2 for an overview of the drivetrain.

The torque delivered from the engine is set by a controller controlling on the difference in actual engine rpm and engine rpm set value. The rpm set value is based on the velocity

error of the vehicle. Engine drive torque and engine brake torque maps are input. The longitudinal differential distributes the torque to the front axle and to the rear bogie axles. Each of the three axles has a transversal differential. All differentials are modeled with coupler constraints and they can be locked during driving using single component forces.

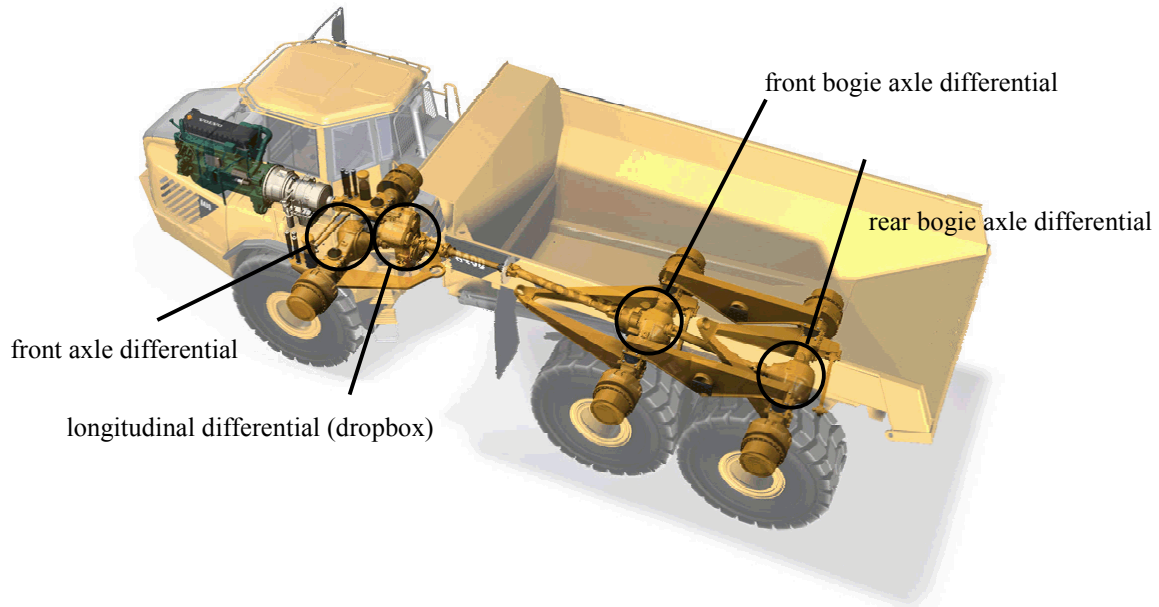


Figure 2. Volvo Articulated Hauler A40D. Overview of differentials

When a differential gets a signal to lock, damping and stiffness coefficients in the single component force are increased from zero with a STEP-function in order to lock outgoing shafts to each other. Equation (1) shows the function expression of a differential lock torque:

$$T_{lock}(t) = k(t)(\alpha_2 - \alpha_1) + c(t)(\omega_2 - \omega_1) \quad (1)$$

where $k(t)$ is the stiffness coefficient and $c(t)$ is the damping coefficient described in Figure 3 below. α is the angular displacement of the outgoing axles and ω is the angular velocity. To release a differential lock the stiffness and damping coefficients are decreased to zero during a short period of time, also using a STEP-function.

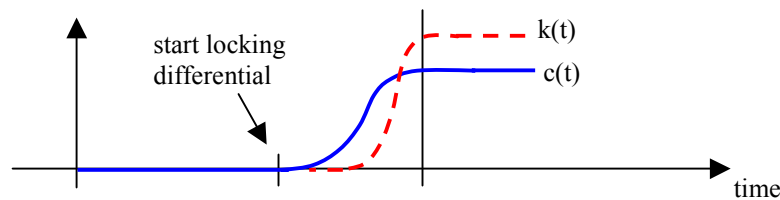


Figure 3. Stiffness- and damping coefficients are increased from zero to lock the two outgoing shafts of a differential

Results

Two simulations are presented in this paper, one in which no differential locking was allowed and one in which the differentials were locked according to Figure 4. The longitudinal differential is locked during uphill driving and when starting to climb the inclined plane in the end of the simulation. The time ranges for the events are:

Dashboard in phase	15-25 sec
Dashboard out of phase	30-40 sec
Right turn, uphill	40-55 sec
Left turn, downhill	60-75 sec
Long U-turn	80-100 sec
Left turn, uphill	100-115 sec
Right turn, downhill	120-135 sec
Wheel track with mud	140-150 sec
Sharp U-turn	155-165 sec
Inclined plane, 10%	170-200 sec

Total simulated time is 215 seconds. In order to get an understanding of the differences between the two, the following entities have been plotted and compared:

- Power delivered to ground for each tire $P_{ground,i} = F_{x,i} v_{x,i}$ where $F_{x,i}$ is the longitudinal tire force of tire i
- Sum of integrated slip of all six tires $\sum_{i=1}^6 \int_0^t ABS(tire\ slip_i) dt$
- Torque in longitudinal and transversal drive shafts

The first plot (Figure 4) shows how the longitudinal and transversal differentials are locked during the second simulation.

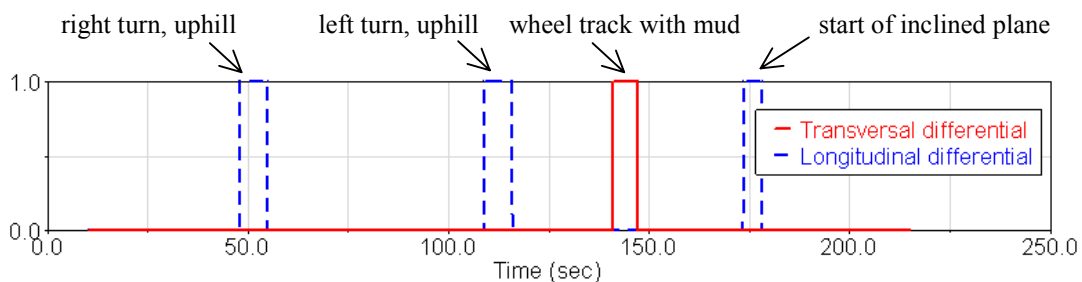


Figure 4. Lock signals for differentials. Front axle transversal differential (red) and longitudinal differential (dashed blue)

Figure 5 and Figure 6 below shows the power delivered to ground from each of the six tires for the two drive cases. It can be seen from these plots that if no differentials are locked, the front axle tires will do most of the work to pull the vehicle up the hill. When

the longitudinal differential is locked the distribution of tractive pull between front and rear axles is different. The front axle tires start to pull the vehicle up the slope, but as the vehicle climbs up the hill the tires of the rear axles do more and more of the work to pull.

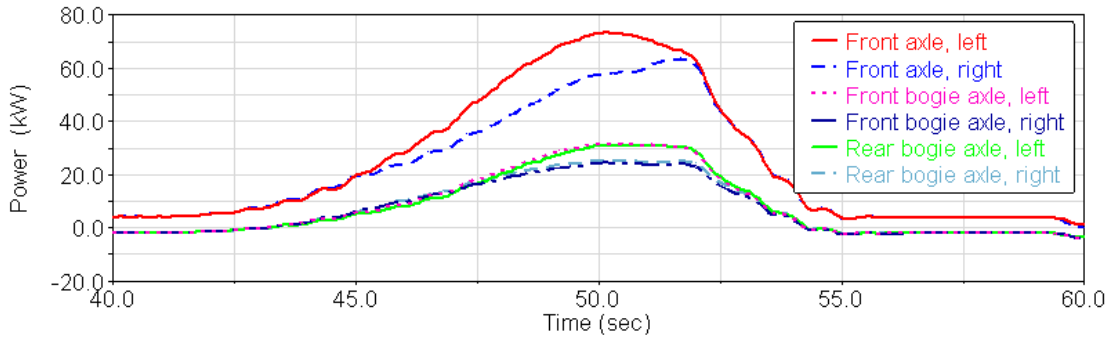


Figure 5. Power delivered to ground. Right turn, uphill. No differentials locked

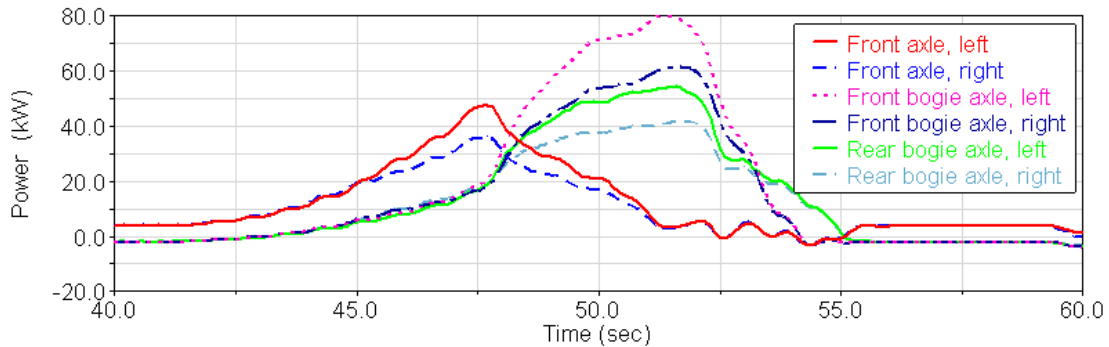


Figure 6. Power delivered to ground. Right turn, uphill. Differentials locked according to Figure 4

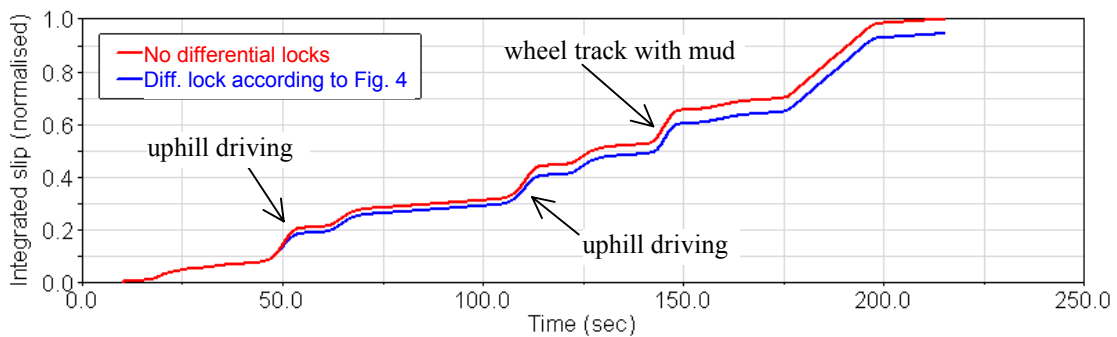


Figure 7. Integrated slip of all six tires

As a measure of how efficient the driving is, the total integrated tire slip is calculated and plotted for the two drive cases, Figure 7. The result is that driving with locked differentials in uphill and driving in the wheel track is slightly better than driving with no differential locks, the sum of the slip over the six wheels is lower, a difference of approximately 5-6%.

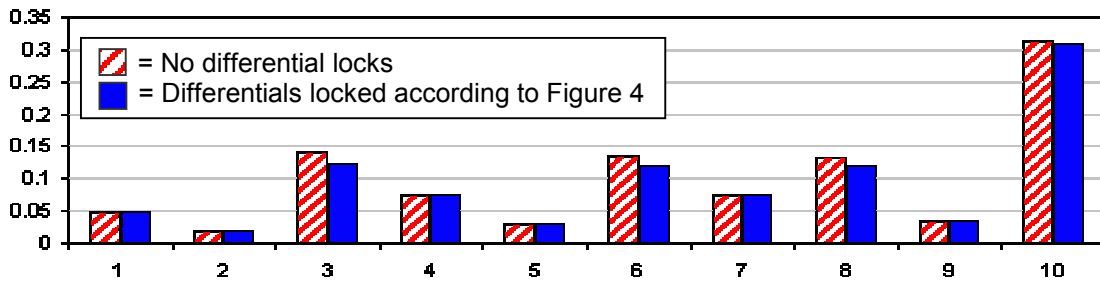


Figure 8. Contribution to the total integrated tire slip from the driving events described in Figure 1

The higher effectiveness of driving, with allowed differential locking, gives us not only benefits. The locking causes higher torques in some driveline components (Figure 9 and Figure 10). When locking the longitudinal differential the torque in the longitudinal drive shaft from dropbox to rear axles are increased by approximately a factor of 2 when turning during uphill driving. On the other hand, the torque in the transversal drive shafts on the front axle is decreased when the longitudinal differential is locked. This is an effect of the different distribution of the power delivered to ground, see Figure 5 and Figure 6. The tires of the bogie axles give more tractive pull and the torque therefore decreases in the front axle drive shafts. For the same reason the torque in the drive shafts of the bogie axles increase.

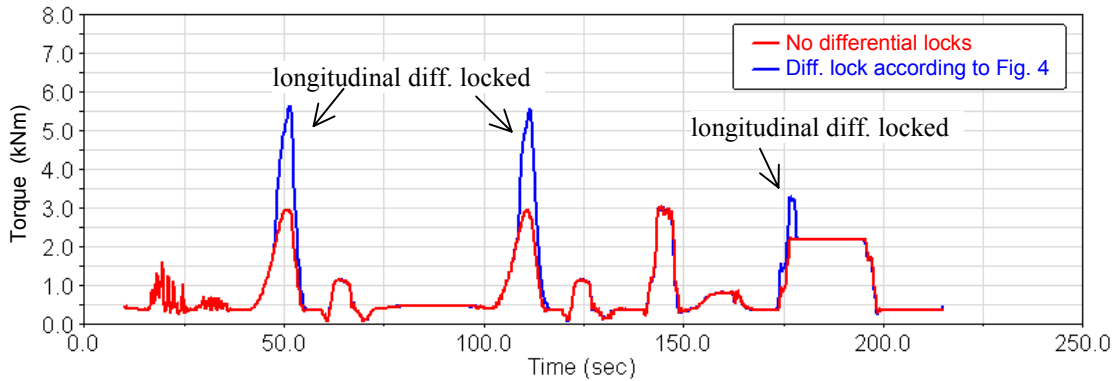


Figure 9. Torque magnitude in longitudinal drive shaft, from dropbox to rear axles

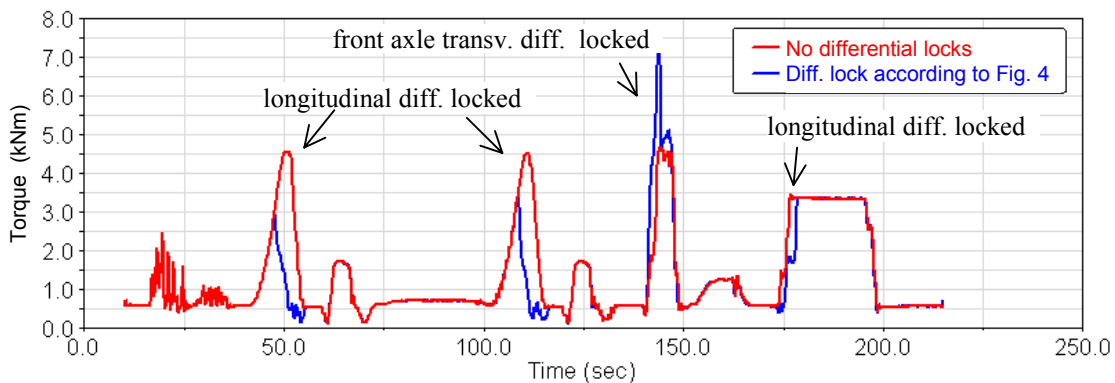


Figure 10. Torque magnitude in transversal drive shaft, front axle right side

Conclusion

The customised ADAMS application is a tool to investigate the effectiveness of Volvo Articulated Hauler's machines under off-road driving conditions. In reality these conditions can vary from road-like to very rough terrain. This tool gives the user valuable information of the performance of the vehicle and it will help Volvo to find a good compromise between traversability and driveline loads under these different conditions.