

**EVS25**  
**Shenzhen, China, Nov 5-9, 2010**

## **Modular driveline concept for underground mining loader**

TEEMU LEHMUSPELTO<sup>1</sup>, MATTI HEISKA<sup>2</sup>, and ANTTI LEIVO<sup>1</sup>

<sup>1</sup>*Department of Engineering Design and Production, Aalto University School of Engineering,  
Puumiehenkuja 5A, Espoo, FI-02150, Finland  
E-mail: teemu.lehmuspelto@aalto.fi*

<sup>2</sup>*Department of Automation and Systems Technology, Aalto University School of Electrical Engineering,  
Puumiehenkuja 5A, Espoo, FI-02150, Finland*

---

### **Abstract**

This paper is part of an ongoing HybLab project funded by the Multidisciplinary Institute of Digitalization and Energy (MIDE) of Aalto University School of Science and Technology. First results and plans were presented in EVS24 [1]. The focus in this paper is to describe what kind requirements must be taken in to account when designing and dimensioning an electromechanical driveline for an underground mining loader. For case work machine is chosen 18t loader which was presented in EVS24 [1]. Also concept for a modular driveline concept will be presented. Basic idea in the concept is to avoid over dimensioning of electric drives by using electromechanically actuated mechanical links between the drive units. The concept gives possibility to optimize dimensioning of each electric drive in driveline so that the best efficiency is in use in normal mean power drive conditions. When one drive needs peak power then mechanical power can be driven via mechanical links from other drives. Disengageable mechanical links gives also possibility to avoid internal counter-torques in driveline caused by steering geometries and differences in tire diameters. The concept will be presented in the EVS25. The first results and experiences from the electromechanical driveline will be presented in EVS26. *Copyright EVS25.*

*Keywords: series hybrid, electromechanical driveline, underground mining loader*

---

## **1 Introduction**

This paper is focused to describe what kind requirements must be taken in to account when designing and dimensioning an electromechanical driveline for the case machine type of mobile work machine. Also concept for a modular driveline concept will be presented.

## **2 Basic Data**

The Case machine was presented more detailed in the EVS24 [1]. This chapter tells short version of the basics.

### **2.1 Case machine**

The case work machine is a frame steered underground mining loader. The loader total weight is 18t with 4t duty load. Maximum speed is 12km/h. In the conventional production version the engine power is 90kW. The engine drives two hydraulic pumps; one for traction and one for

implement hydraulics. Driveline is based on hydrostatic transmission with individual axle motors. Also bucket functions and steering are based on hydraulics.

### **2.2 Duty Cycle**

Typically underground mining loaders gets mined rock from ends of mine caverns and brings it to main tunnel where the load will be dumped to a dumper-truck or conveyor. Driving distance for loaders is typically 200-400m and slopes in caverns are typically between 0-20%. The duty cycle, chosen for the project, is described in the fig. 1.

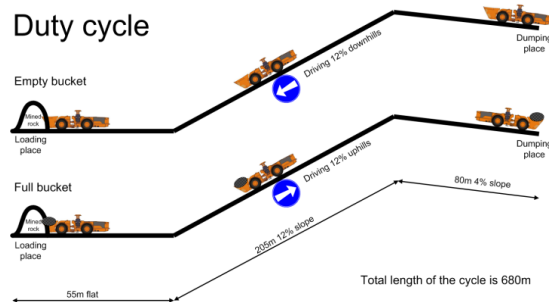


Figure 1: The chosen duty cycle for the loader

The cycle consists of eight phases (Table 1). The last phase ends-up to the same place where the first phase starts again. In real mining conditionings biggest changes between cycles exist in the phase 4 because the rock pile is not homogenous which causes changes in mass of load and time of loading. Other phases are very accurately repeatable.

Table 1: Action on each phase of duty cycle

Cycle phase	Action
Ph1	Driving 4% up-hill (empty bucket)
Ph2	Driving 12% down-hill (empty bucket)
Ph3	Driving on flat (empty bucket)
Ph4	Loading the bucket
Ph5	Driving on flat (full bucket)
Ph6	Driving 12% up-hill (full bucket)
Ph7	Driving 4% down-hill (full bucket)
Ph8	Dumping the bucket

Driving speed in duty cycle is limited to 15km/h which is quite generally used speed limit in mines.

### 3 Requirements for the driveline in loader type of work machines

Loader type machines have some specific features which have influence for driveline; the loading situation, frame steering geometries, differences in axle loads and differences in tire diameters.

#### 3.1 Loading specific requirements

For a loader type work machine the driveline requirements differ quite much compared to other type work machines. Most of the loader specific requirements are related to loading situation. Especially mining loader's typical loading situation is very extreme because rock piles consist of big and heavy stones which are not coming to the bucket easily like homogenous material, e.g. sand, would come. Time frame to take a load to the bucket from a rock pile is about 30-60 seconds and all that time the loader pushes to the rock pile basically in zero speed with full traction force and at same time pumps with the bucket to improve penetration into the rock pile. The bucket pumping

causes big changes in axle loads and normally one of the axles in turns is all the time on air (fig. 2). When both axles has own motor and no mechanical drive axle between, then full traction power is in use only when both axles are on ground. When one of the axles is on air then total traction power is cut to half. That can be avoided if there is possibility to mechanically connect the axle drives on these situations.

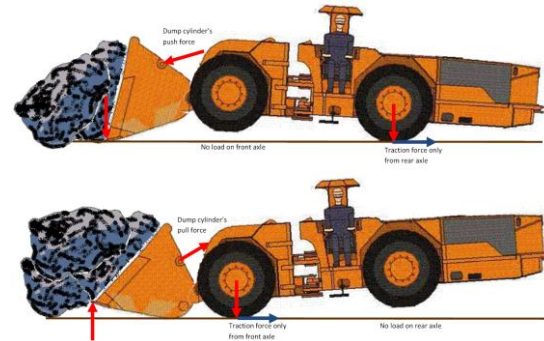


Figure 2 Penetration to the rock pile to get load to the bucket requires full traction force and same time pumping the bucket with the dump cylinder. The bucket pumping has significant influents for axle loads between the axles.

For traction system, loading situation means that motors must be capable to keep up high torque in zero speed up to 1 minute and after that still to be capable to drive the load up to the main tunnel. For an electric motor this type use is not a problem because electric motors have typically good peak power/torque capability. When designing motor use so that also power/torque areas above nominal values are in use then comprehensive thermal calculations for the motor and for the cooling system are needed to make sure that motor thermal profile stays in acceptable level. Also advanced controls strategy for the electromechanical actuators in driveline and for system protection against overloads is very important especially when expected service hours of underground mining loaders are up to 30000h.

To get full traction power during loading it's essential to have possibility to drive mechanical power between axles. This enables to drive all driveline power to the axle which is on ground and thus avoid situation where traction force is cut to half.

#### 3.2 Internal counter-torques in driveline

Internal counting forces in drivelines occur in machines which has mechanical drive shaft between axles and no central differential gear (fig. 3). Most of the loaders have that kind of driveline. The case machine is an exception because it has hydrostatic driveline with one motor per axle and no drive shaft between. The internal counting forces have negative

influence for efficiency, for performance and for tire wearing.

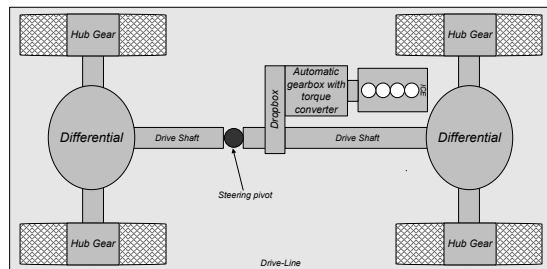


Figure 3 Conventional drive-line. Most of the loaders have this kind driveline.

Steering geometries and tire diameter differences between the axles causes speed differences between the axles. In frame steered machines the problem can be avoided if the pivot point is longitudinally in center of machine which compensates speed differences between the axles during turnings. It seems anyway that the pivot point is not always in center in mining loaders, that's also the situation in the case machine (fig. 4).

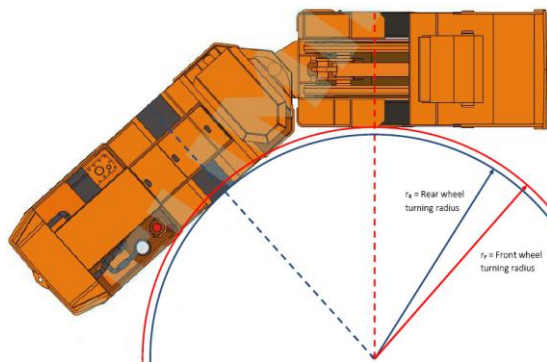


Figure 4 Longitudinally noncentral pivot point causes speed difference between the axles during turnings.

Tire diameter difference can be quite remarkable between axles when one axle has new tires and one axle has worn tires. Thickness of wearing-surface in mining loader tires are normally about 100-150mm. Other matter which has influence for tire diameters is load difference between the axles which has influence for dynamic rolling diameter. In case machine the front axle load varies 4t depending is the bucket full or empty. At same time rear axle load becomes lighter because of gearing effect; load in the bucket is in front of the front axle. Also uphill has influence for axle loads by increasing front axle load because the machine goes up backwards when load is on.

To avoid internal counter forces it's essential to have possibility to disengage the mechanical link between axles during the machine is driving. Also good controllability of speeds and driving forces on

both axles is essential to minimize counter force effect in driveline.

## 4 Driveline concept

The basis for the driveline design work has been described on chapter 3. Also other type work machines have been studied to see what kind requirements those have. Main focus has been anyway to find solution for loader type use.

The concept consist of 3 main parts; high efficiency high speed electric motor, high speed gear-box which can be 1 or 2 speed version and electrically controllable actuator which is used to control gear shifting and mechanical links in the driveline. The main parts will be designed so that parts are scalable to higher power classes and adaptable to different torque/speed levels. Interfaces between the main components remain always same despite different power classes which make the concept modular. Possibility to use existing standard interfaces e.g. SAE interfaces will be studied.

The driveline concept is based on series hybrid construction. In the case machine the construction will be; one motor per axle and 2-speed gearboxes on both motors. Between axles is a controlled power link which allows to transfer power between axles (fig. 5).

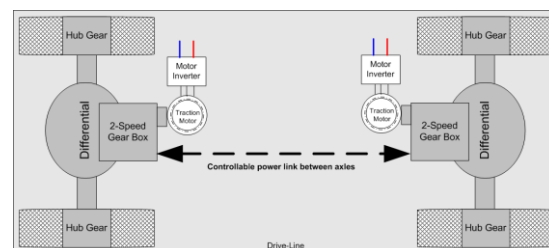


Figure 5 Driveline concept for loader's hybrid version

The mechanical link between the axles will be used normally only during loading. This makes possible to drive torque from both motors to the axle which is on ground. When loading is done then the mechanical link will be opened and both axle can be used freely with them own motors and no counter torques will exist in any circumstances. The 2-speed gearbox between motor and differential is needed to make possible to have high torque during loading and to have high speed during hauling. It also gives better possibility to optimize efficiency and motor dimensioning.

## 5 Dimensioning basis

Basic construction of the case machine's hybrid version will remain same as the conventional version. Small differences in weight and weight distribution might exist but it's expected that this will have no influence for performance.

Dimensioning basis for the hybrid loader's power line will be the conventional loader's total power and measured power distribution. The hybrid version will have same level of nominal power in main drives like; traction drive and implement hydraulics drive. To achieve same performance as the conventional has then also total power downsizing would be possible. But when keeping the power at same level it will be then possible to compare also how much the performance can be improved in addition to energy savings. Because of energy buffers, batteries and supercaps, the hybrid version will be capable for higher total power but during test drives the power can be limited to same level as the conventional version has.

The conventional loader has total power 90kW which is same as the ICE power. The engine is driven with constant speed and the cooling is directly related to ICE-speed which means that cooling and other auxiliaries takes about 20kW power all the time. Implement hydraulics includes also steering cylinder which must be active all the time. Even though the steering power is not big, it has anyway remarkable influence for energy consumption. Based on measurement it seems that replacing hydraulic steering with electromechanical steering would give about 6% energy savings [2]

Table 2 Power distribution in conventional and hybrid versions

Power comparison	Power distribution			
	Total	Traction	Implement hydraulics	Aux
Conventional loader	0-90kW	0-70kW	0-70kW	15-20kW
Hybrid loader nominal area maximum (60sec)	0-112kW ~280kW	0-80kW 110kW	0-40kW 55kW	0-10kW

## 5.1 Dimensioning basis for the hybrid driveline

During hauling operation the traction power and auxiliary power are used at same time so total power will be shared between them. In the conventional version traction gets about 70kW and rest of the power, about 20kW, goes to auxiliary devices. In the hybrid version continuous traction power will be 80kW and auxiliary power about 10kW.

Because both axles will have own motor then continuous power per motor will be 40kW. To achieve high traction force during loading and high

speed during hauling the motor must be capable for high torque at low speeds and wide speed range. Continuous traction power must be limited normally to the motor's nominal power. Preliminary motor curves are presented in the fig. 6.

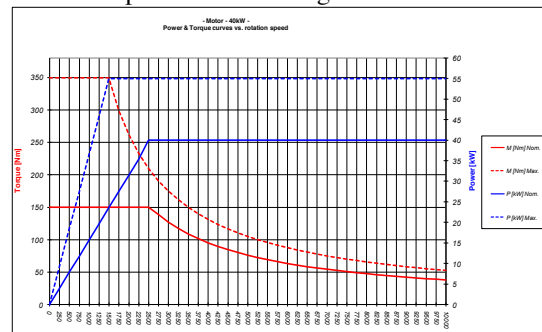


Figure 6 Motor curves for traction motor

Electric motor drives in the hybrid version gives possibility to use also overloading in some situations. That kind of situation is for example loading which needs a lot of traction force in timeframe 30-60sec. Overloading can be used also to achieve better acceleration and to give boost when the loader has to go over some obstacles e.g. fallen stones, on mine track.

Based on calculations the mean power during the duty cycle is about 40kW. That gives possibility to use same motor in gen-set use as the traction motor is. Diesel engine's speed range in industrial engines is usually only up to 2200rpm but in smaller power diesel series e.g. 40-60kW, speed range is usually wider e.g. up to 2500rpm or even 3000rpm so 40kW electric motor's nominal point 2500rpm fits fine for gen-set use with same power class diesel engine.

## 5.2 Dimensioning basis for the implement hydraulics

Implement hydraulics in a mining loader type machine is active relatively short periods. Mean power is also quite low even though power peaks can be quite high. In the conventional version implement hydraulics are needed also for steering which means that pump must be running all the time. For the hybrid version is considered to implement electromechanical steering so implement hydraulics pump needs to be running only during loading and dumping operations.

Even though the 40kW traction motor is a bit too powerful for pump drives in implement hydraulics' circuit, its anyway attractive option for that use too. Short term load-profile gives possibility to use simple air cooling for the motor which reduces available power but still fulfills power requirements what is needed to drive the implement hydraulics pump. It's also beneficial if the loader has only one type motor

for all main functions because that reduces the number of different components.

### 5.3 Dimensioning basis for the auxiliary power

Auxiliary power will be reduced about 10kW by using electrically controlled electromechanical actuators in the cooling system. Also improved total efficiency and about 50% down-sized ICE will reduce cooling needs which gives possibility to use down-sized cooling devices. Also the fact that cooling devices can be used from high voltage side gives possibility to improve efficiency because currents can be kept much lower then.

Better efficiency can be achieved also in low voltage side when 24V will be converted from high voltage side with DC-DC converter which has better efficiency than traditional ICE driven alternators.

## 6 Expected performance

Best way to describe loaders performance is to define how many tons per kilowatt-hour [t/kWh] or how many tons per hour [t/h] the loader is capable to process from rock pile to dumping place.

Improved efficiency and better system controls leaves more power for traction. Two speed gearbox makes possible to achieve higher speeds. Also the conventional loader would have potential to achieve higher speed with two speed gearbox instead one speed which it originally has.

Based on calculations [1] and simulations [3] it seems that a higher speed actually improves efficiency. When cycle time is shorter then energy consumers which uses energy all the time has less time to consume energy so amount of energy used per cycle is then smaller. In the speed range 0-30kmh is no significant increase in traction resistances, like tire resistance, so even if the top speed would be doubled the traction resistances remains at about same level. In the table 3 is shown how much only speed has influence for energy efficiency during one cycle. Assumption in this comparison is that gear ratio in each selected top speed case is optimal for the traction motors. In the first two columns are presented speeds which are possible for the conventional case machine and in the next columns are presented speeds which are possible for the hybrid version.

Table 3 Performance vs. efficiency when only influence of speed is taken into account

Performance vs. efficiency when only influence of speed is taken into account		Measured speeds from the conventional case machine	Speeds are based on case machine's tech. specs	Limited by 15km/h speed limit in mine tunnels	Limited by hybrid version's nom. traction power and max. motor speed	Limited by hybrid version's max. traction power and max. motor speed (this performance level cannot be used continuously)
Speed [km/h] in different phases of the cycle	Ph1	8	12	15	23	30
	Ph2	9,5	12	15	30	30
	Ph3	8	12	15	30	30
	Ph4	0	0	0	0	0
	Ph5	8	12	15	30	30
	Ph6	5	7,5	9	9	12
	Ph7	8	12	15	30	30
	Ph8	0	0	0	0	0
Cycle time <sup>1</sup> [sec]		417	311	266	212	189
Energy per one cycle for whole machine [kWh]		3,45	3,16	3,03	2,89	2,82
Prosentual energy consumption difference to reference value		+13,9	+4,3	ref	-4,6	-6,9

<sup>1)</sup> Includes also loading (Ph4) and dumping (Ph8) times (together 70sec)

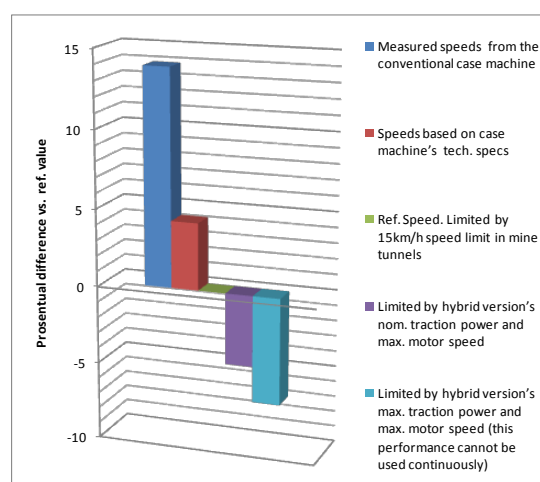


Figure 7 Performance vs. efficiency when only influence of speed is taken into account

The cycle time shows that effective way to improve performance is to use higher speed. Other way to improve performance would be to take bigger loads but that would mean then also bigger machine and probably also bigger tunnels so this option is out of scope. In the tunnels where loaders haul rock, speed is usually limited for safety reasons. Quite often used speed limit is 15km/h. In main tunnels the limit can

be higher so it's desired that the loaders top speed is anyway at least about 30km/h. Increasing speeds in small tunnels would need improved driving controllability and also improved driving comfort. The case machine begins to be quite difficult to drive over 10km/h speed especially on bumpy roads because of primitive steering and uncomfortable cabin where driver and user interface moves back and forth.

Up-hill is the most time consuming phase in the duty cycle. Only way to increase speed on up-hill is to get more power for traction. When total power remains about same, then only way to get more traction power, is to improve efficiency in whole driveline.

Also loading and dumping has some potential to increase performance. Improving these phases needs anyway also improvement for bucket usage. For example if penetration to the rock pile can be improved then time and power needs can be reduced.

## 7 Conclusions

To get full traction power during loading it's essential to have possibility to drive mechanical power between axles. This enables to drive all driveline power to the axle which is on ground and thus avoid situation where traction force is cut to half.

To avoid internal counter forces it's essential to have possibility to disengage the mechanical link between axles during the machine is driving. Also good controllability of speeds and driving forces on both axles is essential to minimize counter force effect in driveline.

Increasing driving speeds reduces energy consumption during work cycle. Higher driving speed requires improvements for drivability and driving comfort.

## References

- [1] Teemu Lehmuspelto, Matti Heiska, Antti Leivo and Ari Hentunen, Hybridization of a Mobile Work Machine, World Electric Vehicle Journal Vol. 3 - ISSN 2032-6653 - © 2009 AVERE
- [2] Matti Heiska, Teemu Lehmuspelto, Antti Leivo and Ari Hentunen, Implementation of Work Hydraulics in Series Hybrid Electric Mobile Work Machine, Seminar of 'Hybrid electric transmission in mobile machines', Aalto University, Espoo, 2010
- [3] Antti Lajunen, Antti Leivo, Teemu Lehmuspelto, Energy consumption simulations of a conventional and hybrid mining loader, EVS25-conference, Shenzhen, 2010

## Authors



### **M.Sc. Research Scientist. Teemu Lehmuspelto**

Vehicle Engineering Design and Production, Aalto University School of Engineering P.O.Box 4300, FI-02150 Espoo, Finland  
Tel: +358503161041 Fax: +358 9 451 3469 Email: teemu.lehmuspelto@aalto.fi

Teemu Lehmuspelto received his M.Sc. degree in mechanical engineering from Helsinki University of Technology (TKK) in 2001. He has been working as a R&D Engineer 2001-2008 in Patria Land & Armament Oy and as a Research Scientist since 2008 in Aalto University School of Science and Technology. His main research interests are vehicle control technologies and hybrid electric vehicle technologies.



### **M.Sc. Research Scientist. Matti Heiska**

Automation and Systems Technology, Aalto University School of Electrical Engineering, P.O.Box 4300, FI-02150 Espoo, Finland  
Tel: +358503011930 Fax: +358 9 451 3469 Email: matti.heiska@aalto.fi  
Matti Heiska received his M.Sc. degree in mechanical engineering from Helsinki

University of Technology (TKK) in 2002. He has been working as a R&D Engineer 2001-2008 in Patria Vehicles Oy and as a Research Scientist since 2008 in Aalto University School of Science and Technology. His main research interests are automation in vehicle control and hybrid electric vehicle technologies



### **M.Sc. Research Scientist. Antti Leivo**

Vehicle Engineering Design and Production, Aalto University School of Engineering, P.O.Box 4300, FI-02150 Espoo, Finland  
Tel: +358503013916 Fax: +358 9 451 3469 Email: antti.leivo@aalto.fi  
Antti Leivo received his M. Sc. degree in automation and systems technology from

the Helsinki University of Technology, Finland, in 2005. He has been working since 2005 as a researcher at the Aalto University School of Science and Technology. His main research projects are in the field of model based software development of hybrid electric work machines.