

LEAN SPEED OPTIMIZATION APPLIED TO A CYCLIC HAUL OPERATION

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ABSTRACT

Cyclic haul operations are iterative transport operations, often performed by several haulers in a production work step. Cyclic haul operations are common in mining and quarry operations where the purpose of the haul work step is to move mass a relatively short distance e.g., from blasted rock supplies to the mass crushing and separation facility. The operation can include one or several haulers that perform the work simultaneously. When several haulers are used, they are generally not synchronized in an optimized way and operative variations and changes continuously affects the operation. An example of such variations can be that the driving speed and time required for certain maneuvers varies depending on driver skills and machine capacity. An operative change can be that the loading position is moved, leading to changed routes and varying distances. The operative characteristics of the haul work step indicates that there rarely exists a static state that the operators can learn to do efficiently. Our previous research has shown that haul operations can have a fuel reduction potential of up to 40%, depending on the operation characteristics and wastes such as unnecessary stops and waiting. This paper presents and assesses a system solution in a decentralized control system that calculates and advices operators with a speed for just in time arrival to a destination. The purpose of the system is to reduce fuel consumption with an obtained production rate. The system assessment shows that while production rate is obtained, fuel is reduced by up to 20% compared to base line operation in a simple quarry haul work step, including three haulers.

KEYWORDS

Haulage optimization, Cooperative ITS, Lean Transportation, Intelligent Transport Systems, Speed Assist, Decentralized Control

INTRODUCTION

In Quarry and Mining operations it is common to have hauling operations that are iterative and cyclic. Cyclic haul operations within the sites has a purpose to move mass short distances from the point of excavation to the mass storage, crushing, screening or facilities. Cyclic haul operations have shown to include operative wastes of up to 30%, which corresponds to an overconsumption of fuel by approximately 30%. The operation can include one or several haulers to perform the work as shown in Figure 1. The operation includes changes and variations such as location of loading and unloading, route characteristics and topology, machine characteristics and different driver skills. The operation capacity is rater discrete due to the limited amount of haulers available leading to a varying amount of operational wastes. The hypothesis of this paper is that waste in terms of waiting time at the destination can be reduced by driving slower aiming at arriving Just in Time (JIT). This reduction in waste can be used on lowering the fuel consumption since a lower driving speed results in less energy consumed. The system consequently use less energy but obtain the same production rate, as long as it is only waste that is removed and not actual production time. To be able to calculate an optimized speed based on JIT arrival in each given situation a set of research questions can be derived:

- How can the future be predicted defining a slot of when the destination is available for the planned activity (load/unload) or to pass a road bottleneck. When will the vehicle ahead in the queue leave the

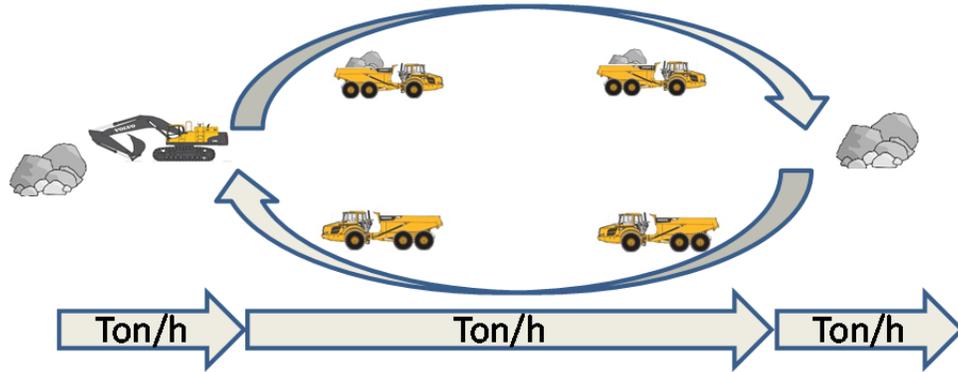


Figure 1 - Balancing cyclic haul work step

slot at the destination and define a (JIT) arrival or simply when is the destination available for the intended activity?

- What activities do the hauler have before it arrives at the destination JIT, of which activities can the time required be estimated?
- What risk do the hauler have of arriving too late and how is risk included in the calculations?
- How can the time left to arrival JIT be used, i.e. how to distribute it over the path to the destination for calculation of an optimized driving speed?
- How can the calculated optimized speed be used to advice or control the vehicle operator (physical or artificial)?

For a system to manage the above tasks it is required to detect, predict and control a large amount of parameters in the flow and manage short lead times from detection to control to be effective.

The need for fast detection and control loops requires sensing and communication capacity at all times and locations during operation. Further the work step, load, haul and unload need to continuously adapt towards the input and output capacity to balance the throughput. From a system and site perspective there are few operational needs to connect to a system outside the operation area. Instead sensor, interfaces and operation data is both produced and consumed locally in the pit. A cyclic haul operation in a quarry or mining environment often consist of a deep pit surrounded by hard rock material in a remote area. Thus, infrastructure based communication cannot be assumed in all locations and situations in the pit. The characteristics and requirements indicate that, in order to be effective, a site-local solution for wireless communication is desired, in combination with a self-learning system that is configurable and adaptive for changes and variations in the operation.

This paper introduces a system solution for JIT arrival in a cyclic haul operation by reducing the driving speed for each individual machine to match throughput of the work step using a decentralized process control system approach. The system of interest is located in each machine and is functional without fixed infrastructure such as access points or base stations. The application logic in each machine is self-learning and self-contained including configuration of the parameters within. The scheduling is individually performed in each hauler based on common operation situation awareness though the continuous communication performed in-between the hauler systems.

By using a decentralized system approach as presented in this paper there are many disadvantages compared to central approaches. Central control has a simpler way of scheduling since it is performed simultaneously and continuously in one place. It is easier to perform fault diagnostics and monitor the operation as well as change and configure scheduling criteria. Unfortunately central control requires a connectivity infrastructure that covers the whole area of the operation. If there are radio shadows resulting in lack in connectivity in e.g., a load area, the loader can never communicate with either the haulers or central systems resulting in a malfunctioned system. If complete connectivity coverage cannot be guaranteed the control and optimization system is not expected to work properly. The benefits with a decentralized approach for the system solution presented in this paper include the system cost that would be required by a centralized network and its components as well as the performance gained by the reliability of coverage in the use of a dedicated short range communication system in-between the haulers. The objective with the system is to decrease speed towards JIT arrival minimizing the waiting time at the destination while minimizing the risk of production loss. By reducing speed and avoiding coming too late which would decrease production rate we expect to lower the fuel consumption without negative effects on the production.

The main contribution with this paper is the assessment of a decentralized system approach for JIT arrival scheduling to destinations for cyclic haul operations in sites and the operational gains in terms of productivity and fuel reductions using real world operation test environments.

The remainder of this paper is structured as follows. In the next section the related work is presented. It is followed by a section describing the method used for the study. Then the analysis of the data collected is presented. The analysis is followed by a section concluding and discussing the results from the study followed by the presentation of future work. Finally the references are listed.

RELATED WORK

As concluded, earlier research has shown that cyclic quarry operation work steps such as load and haul often are characteristic by operative wastes. These wastes are mainly waiting times caused by unbalanced capacities and continuous operative changes. Rylander & Axelsson (2013) quantify the waste to up to 30% of the machine and vehicle time of operation. As concluded by Rylander, Wallin & Axelsson (2014), reduced speed in a typical hauler can reduce fuel consumption with up to 25% and even 40% if there are additional unnecessary stops during haulage. Related work has introduced the operational requirements and system constraints for efficient operation though the wireless communication available assessments and analysis of system requirements for the optimization to be effective. Optimization of underground haulage using centralized scheduling methods have been presented (Pasternak & Marshall, 2016). What is lacking is a system solution assessment of an implementation in a realistic open pit environment, especially using a decentralized approach.

Decentralized and distributed control and scheduling of traffic is still a rather novel approach and not implemented and used in many applications. Traditional control of airplanes and trains are normally done using a centralized traffic controller even though some aspects and local awareness is done distributed (Prevot, 2002). Presented related work in mining operations indicates centralized traffic control architectures. Decentralized approaches to identified traffic control in haulage optimization challenges have not been found. But decentralized systems have been presented in research for other domains and purposes. Recent developments within the Cooperative ITS (C-ITS) and Vehicular ad-hoc networking (VANET) (Hartenstein & Laberteaux, 2010) area have identified a decentralized system approach based on

a common message set that in Europe is referred to as Cooperative Awareness Message (CAM). This message is continuously broadcasted from the host system at a pre-defined frequency. Depending on connectivity solution, available infrastructure and environment the message set is received by other host systems. The host system can based on the awareness message, advice and inform the driver on suitable actions or take direct control of the machine in e.g., platooning applications (Switkes, Boyd, & Stanek, 2014). Other systems that are of similar type are the AIS system for ships, where the system's main purpose is to avoid collisions but also inform about the traffic conditions in the vicinity (Tetreault, 2005). Currently these types of decentralized systems are not utilized for active scheduling in a production system such as Mining and quarry environments.

As presented, there are no identified functional aspects where the centralized approach would be less superior to decentralized control for the purposes stated. Lead and response times including latencies in communication are currently not foreseen as a major issue since the main lead-times in the control loops are the detection and configuration changes mainly affected by coverage and not so much by other wireless communication performance measures such as bandwidth and latency. For a safety critical system on the other hand, those aspects are relevant to consider. Instead the main gains identified with decentralization in the approach taken are the non-functional aspects of system costs, maintainability, system complexity as well as reliability. In this paper the main contribution is not the theoretical benefit analysis in between the system designs. Instead the contribution is the assessment of a decentralized prototype implementation addressing the main targets of the system:

- Decrease waiting time by reducing speed towards destination JIT
- Ensure that the arrival to a value flow bottleneck is not later than the JIT

METHOD

To investigate the knowledge gap described above, there is a need to build and assess the feasibility of operations in real world environments. The method used is to collect empirical data on individual hauler operations through analysis of drive cycles with three articulated haulers. The data was collected using two different driving cycles. First a baseline was created where the drivers freely choose their speed during operation, and secondly the optimized operation data was collected, where the drivers were advised to drive in an optimized speed by the optimization system to avoid waiting by JIT arrival.

The drive cycles were performed in a terrain that is comparable to most quarry operations and consist of dry packaged sand and aggregate material. The empirical study contains iteratively performed test cases to achieve aggregated relevant values. To minimize disturbance factors in the test environment the machine was pre-heated before any data was collected and the operators of the machine made several laps to get familiar with the route and process configuration before the test was initiated. The weather conditions during test were 10-15 degrees Celsius, dry but cloudy conditions.

The data was recorded from the machine's internal Controller Area Network (CAN), where fuel consumption data was collected. The time consumed for the different activities were collected using discrete signals from the weight sensors and tipping body angle. Additionally a GPS and the in-vehicle odometer was used to track the machines on the ground surface.

The data collection was performed using three haulers with slightly different characteristics and size to collect data in a realistic quarry operation configuration. They haulers were operated in a work step

including a load area and a unload area with a relatively flat surface path in between at a distance of ~600m. The operation was performed in two iterations during the same work day and conditions. The loading was performed by a wheel loader and the material consisted of mixed aggregated rock material. Each loading was performed in three iterations for each machine to let them have the same amount of mass loaded. The unloading was configured as general stocking performed on a flat surface without maximal storage capacity. The configuration was set up so that the main bottleneck of the operation was the loader.

The test system consists of the optimization system and a measuring system. The optimization system consists of a decentralized scheduling system where each hauler is scheduling its own parameters based on a continually updated operation awareness. The awareness includes the other haulers' operational data and predicted work step timings, which are continuously communicated over a short range communication system utilizing IEEE 802.11p at 5,9GHz.

The basic components of the optimization system installed in each hauler are:

- Mission manager: The mission manager identifies the destinations and purpose (unload, load) applicable and currently active for the host machine.
- Operation Manager: The operation manager keeps track of the activities within the mission and each activity's predicted execution time finish.
- Vehicle CAN network reader: The component reads CAN signals needed for the test configuration. The signals used are Speed, Fuel, Weight and Tipping body angle.
- Communication manager: The communication manager uses vehicular ad hoc networking to continuously communicate estimated time of arrival (ETA) and time to leave (TTL) for the list of destinations and its activities in the host mission. The communication manager receives the ETA and TTL from all other machines in the process and updates the local process database for the activity timing and process scheduling.
- Positioning unit: The positioning system identifies the current geographical GPS-position of the host machine and map match it to the route chosen.
- Map and route manager: Holds and updates the map of the area and identifies the shortest route to the destination based on the current position. The route manager also includes the capacity and limitations to operate a route segment for the host machine.
- Business logic application: The business logic consists of the logic to calculate JIT to a destination based on the location and predictions of all other machines in the process as well as the overall throughput of the operation. The business logic then uses the route and its limitations to distribute the time left for arrival on the route segments to be able to determine an optimized speed at the current position for JIT arrival.
- HMI display unit: The display unit communicates the optimized current speed advice to the operator of the hauler.

The measuring unit is connected to the system of interest so that timings, activities and sensor activity are logged as well as the actual speed, recommended speed and the fuel consumption. The sensors and fuel consumption are logged from the in-vehicle CAN network at 100 Hz.

ANALYSIS

During the first test cycles without the system the operators of the haulers could drive freely creating an operational base line. During the second test cycles the same operation was performed with the

same machines and drivers with the system enabled. The operators were instructed to follow the speed advice presented for them. To analyze the outcome three questions were formulated:

- Are the drivers following the advice presented while the system is enabled and is the speed decreased by it?
- While the drivers follow the advice, will the system decrease operative wastes as waiting time at the load area/bottleneck of the operation by driving slower?
- Is the fuel consumption less with the system than without?

In the two test configuration operations, actual speed and recommended speed were measured and compared. But a strict analysis of the difference in between the values is not a fair comparison. The system implemented did not fully consider all the physical constraints and variations in the advised speed. Due to the implemented HMI using only a visual interface there were a slight deviation in how accurate the drivers manage to follow the advice. But since the main purpose was to decrease waiting by decreasing speed the average speed should anyway be lower with the system than without. In Table 1, the average speed used for the haulage is presented. Since the hauler transports material one way and goes empty the other the names Loaded and Unloaded is used. Loaded is referring to the haulage with mass material in the tipping body. As seen the actual speed was in between 25 to 40% less while using the system. This can be considered as a general proof that the drivers was following the advice given in a reasonable good way.

Table 1 Average speed used for the haulage activities

	Speed Without System (km/h)		Speed With System (km/h)		Change (%)	
	Loaded	Unloaded	Loaded	Unloaded	Loaded	Unloaded
Hauler 1	28,8	29,6	17,7	17,5	-38%	-41%
Hauler 2	24,3	24,5	17,0	18,4	-30%	-25%
Hauler 3	27,0	29,0	16,7	16,8	-38%	-42%

The second question is answered in Table 2. The bottleneck causing waiting times was the loading area. While we compare the idle times we can see a decrease for all machines while following the advice and driving slower. The definition of the idle time used is the time to enter an area surrounding the load position triggered by a geofence to until the loading starts, which include the initial maneuvering to the load position and waiting at the load position. A geofence can be described as a virtual fence of geo positions defining an area, while crossed a triggering condition can be set. Due to this approach, the idle time cannot be zero, but kept to a practical minimum avoiding waiting times.

Table 2 Timing comparisons at loading activity

	Without system (s)			With System (s)			Change (%)	
	Total Load activity time	Load time	Idle Time	Total Load activity time	Load time	Idle Time	Load Time	Idle Time
Hauler 1	168	93	75	142	94	48	1%	-36%
Hauler 2	179	82	96	134	87	47	6%	-51%
Hauler 3	196	86	110	130	87	43	1%	-61%

The comparison between the test setups shows a decreased fuel consumption that differed in-between the operators and machines while enabling the system. In Table 3, fuel savings per machine and total accumulated fuel in % are presented comparing the base line cycles with the system enabled cycles.

Comparing sensor data over three cycles without system and with system shows a fuel reduction by up to 20% for one vehicle. But the savings differ and one vehicle only had 6% fuel savings.

Table 3 Fuel Savings in %

Hauler 1 average fuel saving/cycle	15%
Hauler 2 average fuel saving/cycle	6%
Hauler 3 average fuel saving/cycle	20%

CONCLUSIONS & DISCUSSION

The purpose with the optimization system described is to minimize operative waste in an iterative haulage operation by decreasing speed using a decentralized system solution. The optimization needs to be done in a way that does not decrease the overall production rate. Since the production rate is defined by the process bottleneck in the theory of constraints (Goldratt, 1990), the bottleneck uptime and production need to be ensured. In the test performed the production rate i.e. bottleneck was defined by the loader. Relatively the loading capacity the haulers then had an over capacity. The operative wastes addressed by the system were then mainly waiting time performed by the haulers at load area. While used, the system successfully decreased the waiting time by adjusting speed during travel towards a future estimated JIT arrival. The decrease was done by reducing the waiting time before the loading activity, where waiting for the previous hauler was performed.

Since different drivers were used and asked them to drive freely during the cycles where the system was not giving advice on speed, the driver performed differently. What was clear was that the driver that had the least average speed and speed difference in between the cycles also had the least fuel saving in average.

The system effectively managed the minor deviations in actual activity timings such as travel times and loading times during operation and continuously updated and adjusted JIT data for its purpose. Real life savings in the test cycle configuration have been presented based on the tests performed. The

system relies on available and accurate wireless communication to continuously exchange operational data so that all machines can adapt to deviations and changes made.

FUTURE WORK

The assessment presented show how a cyclic load and haul operation where the loading activity is the operation bottleneck can be optimized though a decentralized scheduling system. The test configuration shows that a system can be designed that manages natural deviations caused by the operators to decrease waste and save fuel. In the test cycles performed only minor driver based deviations were managed. More tests are required to manage larger deviations in connectivity, and operative changes such as route changes and unexpected breaks. Further the system architecture and the overall scheduling algorithms and timing detection systems will be investigated.

Further validations of the system by longer tests in real world environments are required to ensure that the operative changes done are captured and used effectively in the optimization calculations.

While the optimization is performed the approach taken in this paper is an assistive advice that is presented to the driver. A future improvement could be to integrate the speed advice into a control system that control the speed and driveline to further optimize its performance towards JIT arrivals.

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