Technology Development Decision Economics for Real-Time Rolling Resistance Monitoring of Haul Roads

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Abstract: Proponents of advanced technologies for the delivery of constructed facilities assert that information and automation technologies can significantly reduce construction costs. However, technology transfer has been greatly limited as practitioners are reluctant to adopt new technologies for myriad reasons including concerns over expertise requirements, value versus traditional approaches, implementation practicality, and risk. All of these concerns ultimately relate to cost versus benefit. While considerable automation research has been documented, thorough economic justifications in the literature have been rare in comparison. In this paper, the writers present and illustrate a model to assess the economics of construction equipment automation using a case illustration focused on the allowable cost of sensor technologies for real-time, in-field rolling resistance monitoring. Rolling resistance is vital in determining power train requirements, fuel consumption, and travel time associated with hauling operations. The absence of a true understanding of field changes in rolling resistance may result in a lack of insight regarding the interaction of jobsite characteristics and the performance potential of hauling operations.

DOI: 10.1061/(ASCE)0733-9364(2007)133:5(393)

CE Database subject headings: Automation; Construction analysis; Cost analysis; Construction management; Earthmoving; Economic models; Productivity; Technology transfer.

Introduction

Information and automation technologies are generally viewed as means to significantly reduce costs for the performance of construction activities. In particular, real-time automated data collection from field sensing systems has potential to impact management decision-making and construction performance. However, adoption of real-time data gathering and processing technologies has been hindered by perceptions, or the reality, of such hurdles as concerns over expertise requirements, value versus traditional approaches, implementation practicality, and risk. All of these concerns ultimately relate to the fundamental tradeoff of cost versus benefit. Thus, a compelling argument for any specific automation feature must take into account the potential monetary savings for the contractor as well as the economic benefits for the potential technology manufacturer. While it remains to be seen how significantly construction performance in productivity, safety, and quality of work might be enhanced by steady input from new sources of precise, real-time data and information, the writers believe focusing on obtaining data that influences the *management* of production should be a top priority, as it directly impacts the bottom line in the competitive construction industry where profit margins are, typically, small.

The value of richer inputs to production-oriented decision making in construction has been noted many times throughout the literature. Christian and Xie (1996) indicated the inadequacy of sweeping generalizations that are typically made in estimating the production and cost of earthmoving operations. Kannan and Vorster (2000) have also demonstrated that use of onboard state monitoring instrumentation on construction equipment can be extended to build a company- or project-specific *experience database* for specific truck loading operations. Developed from the contractor's specific projects, their concept of an experience database exploits data obtained via the manufacturers' equipment monitoring systems to enable a break in reliance upon "generic (industry-wide), static, and nonelectronic standards and manuals to dynamic and electronic archives of actual field experience." These efforts, while specifically focused on earthworks, raise a more general question: To what degree might the management of construction operations be impacted by having access to the type of monitoring data (e.g., volume of inputs, machine production rates, error rates) that other production/manufacturing industries take for granted (e.g., automobile manufacturing, chemical processing, semiconductor fabrication)? What are some parameters for which such continuous monitoring might be beneficial in the construction industry? These questions highlight the possibility that obtaining and utilizing information from the field can be made more valuable and practical by focusing on two design principles:

- Data collection efforts should focus on parameters that influence financial and/or management (overhead) decisions.
- Sensing systems used to gather field data, should continuously

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Note. Discussion open until October 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on March 17, 2005; approved on November 16, 2006. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 133, No. 5, May 1, 2007. ©ASCE, ISSN 0733-9364/2007/5-393–402/$25.00.

be in a position to obtain the most relevant and up-to-date information.

In this paper, the writers conceive of using construction equipment as a mobile, field-aware, sensing platform, and in a focused case discussion explore the concept specifically for monitoring a critical variable field parameter affecting the performance of hauling operations—rolling resistance (RR). One of the most important factors in the prediction of production rates, RR is not typically measured but rather treated by tabular estimates and rule of thumb because of the difficulty in obtaining field measurements. RR is vital in determining power train requirements, fuel consumption, and travel time (Smith et al. 2000). Not having a true understanding of field changes in RR leaves managers without detailed insight regarding the interaction of jobsite characteristics and the performance potential of their hauling operations.

A framework for an economic justification that fundamentally tracks the influence of an incremental change in RR with operation time on expense is proposed. Example calculations illustrate the linkage between a selected level of responsiveness to the measured parameter (RR) and the expense that could be justified for a sensing technology solution. The range of options for potential sensing technologies for RR monitoring are beyond the scope of this paper, but can be assessed using the proposed model.

Motivation for Monitoring Rolling Resistance

Total resistance (TR) is the most important site characteristic affecting the performance of haul vehicles transporting material off-road on temporary haul routes (Karafiath 1988). TR is constituted as the sum of RR and grade resistance (GR). RR is the opposition of the level riding surface to the forward or reverse movement of a piece of wheeled equipment. GR is the opposition, due to gravity, to the forward motion of equipment as it moves up a grade. The factors for both parameters are multiplied by the gross machine weight of the equipment to determine the corresponding forces. However, unless the slope of a haul road is modified, only RR represents a time-variable characteristic of the haul road. TR directly impacts the travel speed of a haul unit of given power, and, in turn, the speed of the haul unit determines haul and return travel times, and thus the productivity of a hauling operation. The most common current practice for predicting the travel speed of a haul unit utilizes empirical equations to estimate TR for each distinct section of the haul road and then determines the corresponding haul unit speed(s) from the manufacturer's performance data (Day and Benjamin 1991; Schaufelberger 1999; Nunnally 2004; Peurifoy et al. 2006).

Although GR along a selected route conceivably can be measured with sufficient accuracy, RR presents a more challenging problem for field sensing that has not been pursued. The conditions of haul roads change during the hauling process, often in an inconsistent manner. For instance, greater deterioration is noted to occur where the machines repeatedly accelerate and decelerate in each cycle (Wood et al. 1995). Because of the difficulty (effort) in obtaining field measurements, RR is mostly *inferred* during the process of operation by visual inspection (not actual measurement) of the haul road surface with regard to tire track depth. Actual RR is not known and the magnitude of changes is also a mystery. The absence of a true understanding of field changes in RR may result in losses in production and in higher costs because of inefficiency in the timing of haul road maintenance and improvements.

Current practice of road condition assessment relies upon inference techniques for both "on-highway" and "off-highway" situations. In off-highway settings, visual inspection of road defects (such as corrugations, rutting, and gravel loss) by personnel is the common technique and found to be subjective, time consuming, and error prone. In on-highway situations, surface roughness is the major measure of road conditions for road serviceability assessments using a profilometer or bump integrator (Thompson 1996; Robinson and Thagesen 2004). While multiple studies (e.g., Grahn 1991; Descornet 1990) have confirmed that road surface roughness dramatically affects rolling resistance, this measurement is not suitable for determining rolling resistance in off-road settings since the interactions between the materials of the riding surface (paved versus unpaved) and the characteristics of the operating vehicles (light versus extra heavy) are different. Although no relationship has been established between the surface roughness and rolling resistance for the unpaved haul road under heavy hauler traffic, several empirical relationships are used to link roughness to estimates of rolling resistance for cars, buses, and light and heavy commercial vehicles on paved and unpaved roads (Watanatada et al. 1987; Du Plessis 1990). These infer that RR can also be a good indicator of the unpaved haul road condition. In this light, the writers propose that current sensor technologies provide new opportunities for accurately assessing real-time changes in rolling resistance, instead of inferring its effects through empirical relationships, and also provide an opportunity to learn more about its impact upon off-road hauling productivity.

Implications of RR Monitoring

The haul unit equipped as a real-time, RR sensing platform would provide not only a real-time measurement of RR, but also yield measurements that are linked to the specific location of the work, providing a profile of the haul road condition. This output could facilitate a more strategic application of maintenance (corrective measures) to the more critical locations along the haul route. In addition, the accumulated record of changes in the average rolling resistance would provide a deterioration profile, essentially a fatigue characterization, for the haul road. From such data, an overall strategy for hauling operations and haul road maintenance could be formulated and executed. As illustrated in Fig. 1(a), in a traditional construction setting, a haul road is prepared to a desirable level of RR and then utilized for hauling operations until the time of a prescheduled maintenance operation, or the road condition deteriorates to a point that is readily observed by a field supervisor to be unacceptable. Maintenance is then conducted, which, here, is assumed to return the haul route to its initial desirable RR conditions. This practice, followed strictly, inevitably leads to unnecessary maintenance activities and periods of haul activity during conditions of less than optimal RR. In contrast, enabled by real-time sensor-based measurements of RR, the site manager can be responsive to a critical magnitude of change in RR (ΔRR) and can call for maintenance operations upon the sign of impending deterioration as Fig. 1(b) illustrates. The time (or number of trips) that results in a level of rolling resistance that requires maintenance may not be constant due to factors such as moisture conditions, variations in driver habits, and changes in the magnitude of the load carried by the haul vehicles, but real-time sensing could ensure that proactive maintenance is effectively scheduled.

Since the lack of data indicating the change of RR over repeated hauls and returns brings into question the efficiency of haul road management, a sensing system is desirable that can provide characterization of the haul road as indicated by the RR

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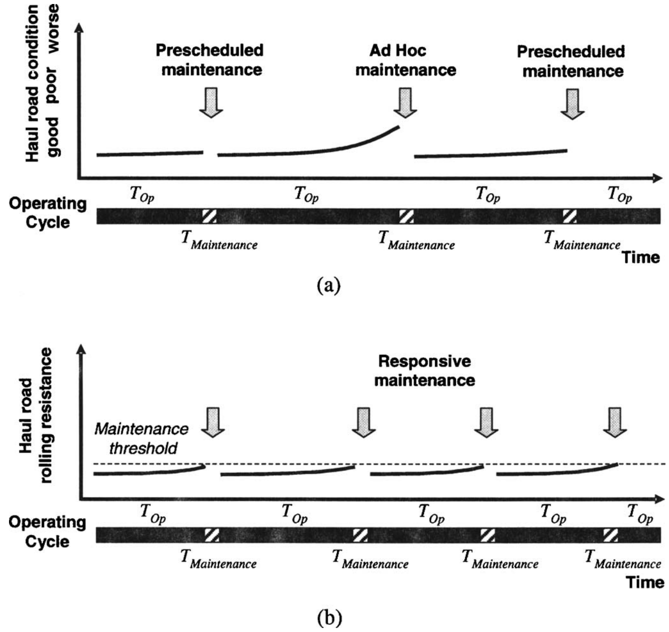

Fig. 1. Transition in haul road RR profile with time: (a) "reactive" haul road maintenance schedule based on field supervisor observation or prescheduled decision; (b) "responsive" haul road maintenance based on real-time sensor data gathering

deterioration. Such an approach is useful for establishing rules of thumb for future operations. Alternatively, even a few samples of such a characteristic variable at the start of a project may suffice to calibrate a sensing system used to manage the remainder of the project.

Conventional Measurement of RR

For different riding surfaces, RR (or the RR factor) may be expressed in kilograms per metric ton of gross machine weight and is fundamentally obtainable for a free-rolling wheel by interpreting data from towing tests on level ground using the following equation:

$$\mathrm{RR} = \frac{\text{Tow cable tension (kg)}}{\text{Total gross vehicle weight (t)}} \tag{1}$$

Tire penetration into the riding surface, internal wheel friction, and tire sidewall flexing are the three parameters that fundamentally lead to RR, but penetration is accepted as the primary indicator, especially for the relatively soft ground surfaces and low speeds associated with heavyweight off-road earth hauling. The leading texts most often refer to a common empirical approach adopted in the *Caterpillar Performance Handbook* (Caterpillar 2000), which assumes a minimum RR based upon tire type and considers only tire penetration as observed in the field as the indicator of additional RR. For radial or dual tire configurations, the empirical relationship is as follows:

$$\mathrm{RR}\ (\text{kg/t}) = 15\ \text{kg/t} + [(6\ \text{kg/t per cm}) \times (\text{cm of tire penetration})] \tag{2}$$

If the tire penetration is unknown, tables can be referenced for typical RR values for various riding surfaces. The values of RR can differ with the type, structure, and moisture of the soil. For example, the RR of an asphalt surface is approximately 20 kg/t, and a dirt surface that is soft or poorly maintained is approximately 60 kg/t (Schaufelberger 1999). Other manufacturers—John Deere (2003), for example—use somewhat different terminologies or factors that nevertheless embody the notion of estimating forces due to riding surface condition and grade to arrive at speed, and thus travel time. Therefore, all of these approaches could ultimately benefit from an enhanced understanding of real-time changes that occur in rolling resistance during field operations.

Questions on Management of Rolling Resistance

As noted above, the haul unit equipped as a real-time, RR-sensing platform would provide not only a local measurement of RR, but also yield a profile of the haul road condition. The following questions should be answered in adopting technology for RR monitoring:

- How much change of RR (ΔRR) should trigger responsive maintenance?
- How rapidly is the ΔRR trigger level reached, i.e., after how many hours or trips?
- Where along the haul route is the ΔRR trigger level reached first, and what percentage of the haul route must reach the ΔRR trigger level to warrant the cost of corrective maintenance?

The answer to the first question will determine the crucial moment for initiating maintenance. If the ΔRR is set high, the number of responsive maintenance occurrences may decrease, possibly resulting in less total disruption of production for maintenance, but at the cost of potentially poor road conditions and reduced productivity. If the ΔRR is set too low, the cost due to poor riding conditions will decrease, however, the maintenance time (period of disruption) may increase dramatically because the frequency of responsive maintenance is high. The answer to the second question could help managers make a decision for selecting an appropriate ΔRR. As noted above, several factors may influence the outcome. Answers to the third question can lead to strategic application of maintenance efforts, since ΔRR may not be uniform along the haul road. Thus the time for maintenance could be carefully regulated and managed. These three questions help to frame the research that could be conducted to economically justify an automated solution for real-time rolling resistance monitoring.

Economic Analysis Model

The basic premise of the model is that typical savings to the contractor provide an estimate of the technology investment expense the contractor will readily tolerate. The original equipment manufacturer or aftermarket supplier of a retrofit item then has a price range within which to work. This approach strives for hard numbers and does not address the extrinsic market influences (e.g., high-tech image) that might lead a customer to pay more than is cost effective within, say, a single project. If the monetary benefits are greater than the costs of a certain sensing technology, it shows that the technology is a cost-qualified candidate warranting further technical consideration.

The model is based on the comparison between having and not having real-time in-field RR monitoring. The savings gained by using new sensing technologies for RR monitoring (S_{RR}) is equal to the difference between total operation cost resulting from use of the new sensing technology ($\mathrm{TC}_{\mathrm{OpSensing}}$) and the total operation cost relying only upon observation or rule of thumb

$(TC_{OpConventional})$. Eq. (3) characterizes this relationship, which assumes that real-time rolling resistance monitoring yields a reduction in operation time by facilitating a lower average RR for the haul road. The detailed explanation of this model and the variables of total operation cost are provided in the following section

$$S_{RR} = TC_{OpConventional} - TC_{OpSensing} \tag{3}$$

Total Operation Cost

As shown in Fig. 1(a), the general case for conventional practice assumes the hauling operation proceeds unrestricted until a predetermined interval of time has transpired or when the perceived ΔRR triggers a clear need for maintenance. At this time, equipment is brought onto the haul road to upgrade the haul road surface and the hauling operation continues with a lower production rate during this maintenance period. The introduction of real-time sensing of changes in RR assumes the disruption for maintenance to occur only when a predetermined level of RR is reached [Fig. 1(b)]. Therefore, the amount of time between consecutive applications of maintenance methods may vary somewhat. The total operation cost (TC_{Op}) is equal to the sum of hourly haul operation cost (HC_{HaulOp}) multiplied by the unrestricted operation (hauling) time (T_{Op}) and the maintenance time $(T_{Maintenance})$, plus the sum of the hourly maintenance cost $(HC_{Maintenance})$ multiplied by the maintenance time $(T_{Maintenance})$ for each operation–maintenance cycle, as shown in Eq. (4)

$$TC_{Op} = \sum_{Cycle=1}^{n} [HC_{HaulOp} \times (T_{Op} + T_{Maintenance})]_{Cycle} + \sum_{Cycle=1}^{n-1} (HC_{Maintenance} \times T_{Maintenance})_{Cycle} \tag{4}$$

It is acknowledged that an increase in required rimpull due to greater RR leads to an increase in the real hourly cost of haul unit operation. However, the significance of this relationship is regarded as negligible and actually not recognized in practice since a single hourly cost is assumed for the equipment over the duration of an entire project. That is, a contractor will not typically change the estimate of HC_{HaulOp} for a specific haul unit during the course of a project. HC_{HaulOp} includes all the costs related to operation such as labor cost, fuel consumption, and ownership cost. Although some contractors suggest that $HC_{Maintenance}$ is, typically, charged for the full duration of the project or operation regardless of their actual utilization during that time period, the $HC_{Maintenance}$ is charged only for the maintenance period for the purpose of the analysis. That is, the focus is on cost rather than pricing. The critical assumptions for the general case then can be described as follows:

- Maintenance equipment is being charged only for actual maintenance periods.
- HC_{HaulOp} and $HC_{Maintenance}$ are constant for the project or analysis period.

Based on these assumptions, Eq. (4) can be simplified, using the total time of operations, TT_{OP} and the total time of maintenance, $TT_{Maintenance}$, as follows:

$$TC_{Op} = HC_{HaulOp} \times TT_{Op} + HC_{Maintenance} \times TT_{Maintenance} \tag{5}$$

where

$$TT_{Maintenance} = \sum_{Cycle=1}^{n-1} (T_{Maintenance})_{Cycle} \tag{6}$$

and

$$TT_{Op} = \sum_{Cycle=1}^{n} (T_{Op})_{Cycle} + \sum_{Cycle=1}^{n-1} (T_{Maintenance})_{Cycle} \tag{7}$$

A *cycle* represents an occurrence of hauling and any subsequent maintenance operation. Each cycle begins either at the start of the project or after the end of a maintenance application. The total number of hauling cycles (n) is greater than that of maintenance cycles $(n-1)$, representing the assumption that the project will not end with a maintenance activity. The accumulated volume of work (ΣV_{Work}) at a certain cycle is the sum of the accumulated volume of work on regular (unrestricted) hauling cycles (V_{OpWork}), and the accumulated volume of work during maintenance (V_{MWork}). The cycles, n, can be obtained by setting this sum equal to the total volume of work for a project (TV_{Work}), as shown in Eq. (8)

$$TV_{Work} = \sum_{Cycle=1}^{n} (V_{OpWork})_{Cycle} + \sum_{Cycle=1}^{n-1} (V_{MWork})_{Cycle} \tag{8}$$

It is evident that TT_{Op}=primary variable quantity in Eq. (5), and as noted in reference to Eq. (3), is expected to be less when real-time sensing is implemented. This improved TT_{Op} is achieved by reducing the average level of RR and increasing productivity during the entire operation. An examination of the critical relationships in the economic analysis for TT_{Op} and RR is presented in the next section.

Operation Time and RR

The unrestricted operation (production) time for any given cycle, T_{Op}, is found by dividing V_{OpWork} by the average productivity during a cycle. The capacity (Cap_{Haul}), the operational efficiency (E_{ff}), and the cycle time of a haul unit are the required parameters for the calculation of productivity. The cycle time includes travel time and fixed time (T_{Fix}). Travel time is determined by the distance (D) divided by the travel speed (haul and return). T_{Fix} is the sum of the loading time, the dumping time, and the spotting time. Thus, T_{Op} can be presented by Eq. (9)

$$T_{Op} = \frac{V_{OpWork}}{\text{Productivity}} = \left(\frac{D}{SP_{Loaded}} + \frac{D}{SP_{Empty}} + T_{Fix}\right) \times \frac{V_{OpWork}}{E_{ff} \times Cap_{Haul}} \tag{9}$$

where SP_{Loaded}=haul speed; and SP_{Empty}=return speed for the hauler.

The standard relationship between maximum speed and total resistance (or required rimpull) is given by the Eq. (10) (Peurifoy et al. 2006)

$$\text{Speed} = \frac{(274)(\text{HP})(E\,\%)}{\text{TR Force}} \tag{10}$$

where 274=metric scale constant; HP=horsepower of the haul vehicle engine; and $E\%$=mechanical efficiency of the haul vehicle drive train.

For a level riding surface (zero grade), the TR force will be equal to the force due to RR, which is the product of the gross machine weight and RR. If the quotient of the product in the

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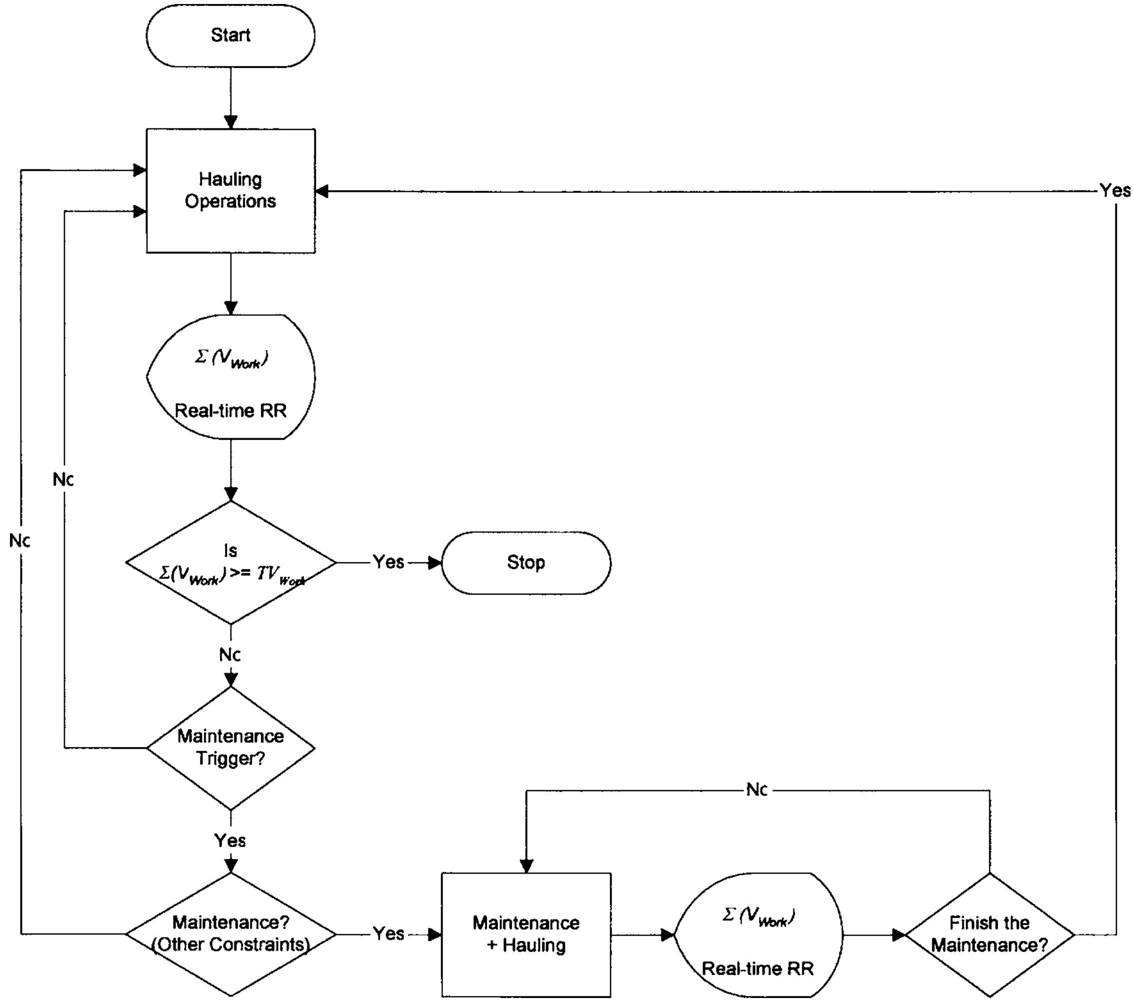

Fig. 2. Logic for MATLAB-based simulation

dividend of Eq. (10) and the gross machine weight in the divisor—all parameters that characterize the haul unit—are represented by M, then it can be said that

$$\text{Speed} = \frac{M}{\text{RR}} \tag{11}$$

Thus, the relationship between T_{Op} and RR can be described as follows:

$$T_{\text{Op}} = \left(\frac{D}{M_{\text{Loaded}}/\text{RR}} + \frac{D}{M_{\text{Empty}}/\text{RR}} + T_{\text{Fix}} \right) \times \frac{V_{\text{OpWork}}}{E_{ff} \times \text{Cap}_{\text{Haul}}} \tag{12}$$

Total Operation Cost and RR

The basic relationship of Eq. (12) can be substituted into Eq. (5), so that TC_{Op} becomes

$$\text{TC}_{\text{Op}} = \text{HC}_{\text{HaulOp}} \times \sum_{\text{Cycle}=1}^{n} \left[\left(\frac{D}{M_{\text{Loaded}}/\text{RR}} + \frac{D}{M_{\text{Empty}}/\text{RR}} + T_{\text{Fix}} \right) \times \frac{V_{\text{OpWork}}}{E_{ff} \times \text{Cap}_{\text{Haul}}} + T_{\text{Maintenance}} \right]_{\text{Cycle}} + \text{HC}_{\text{Maintenance}} \times \text{TT}_{\text{Maintenance}} \tag{13}$$

It is also important to note that as a haul road's rolling resistance increases, more time is required to restore the haul road to its initial RR level. That is, $\text{TT}_{\text{Maintenance}}$ is also a function of RR. While the literature does not provide a relationship between these parameters, it is evident that a discrete number of passes by a motorgrader to perform haul road maintenance will apply to reducing a range of rolling resistance levels to a target RR.

Cost Savings and RR

The basic relationship of Eq. (5) can be incorporated into Eq. (3), so that S_{RR} becomes

$$S_{\text{RR}} = \text{HC}_{\text{HaulOp}} \times (\text{TT}_{\text{OpConventional}} - \text{TT}_{\text{OpSensing}}) + \text{HC}_{\text{Maintenance}} \times (\text{TT}_{\text{MaintenanceConventional}} - \text{TT}_{\text{MaintenanceSensing}}) \tag{14}$$

As inferred in Fig. 1, it is likely that the new haul road maintenance strategy which arises from real-time sensing results in different time periods (durations) for the unrestricted operation (difference in the first term) and maintenance (difference in the second term) cycles. That is, a sensor-based system can provide the RR data as an input for the maintenance decision analysis to help managers achieve the minimum total operation cost by revealing the optimal maintenance threshold (RR trigger). For a conventional maintenance strategy, since RR (or the change in RR) is unknown to managers, the haul roads are maintained on

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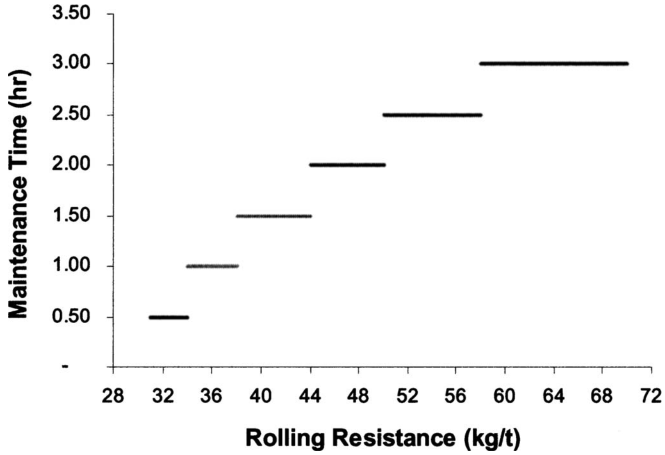

Fig. 3. Maintenance time with the change of rolling resistance

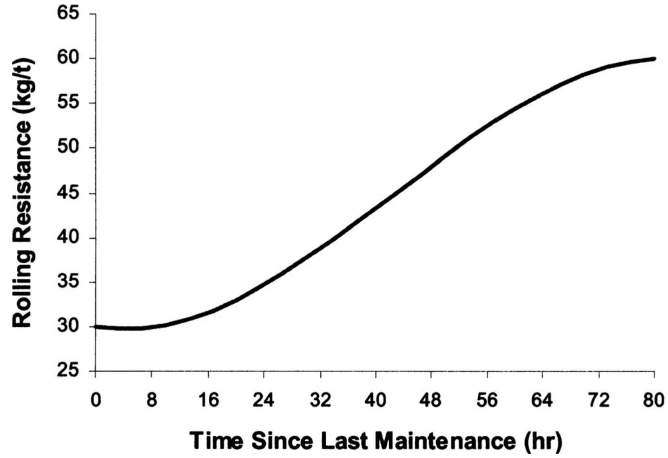

Fig. 4. Hypothetical profile of rolling resistance resulting from a hauling operation cycle

either a predetermined or ad hoc schedule according to manager experience. The $TC_{OpConventional}$ is, therefore, variable based on the quality of planning and management regarding haul road maintenance. A detailed comparison of cost savings calculated using the above outlined formulations in conventional and sensing scenarios is presented in the following case illustration.

Case Illustration

The following hypothetical case is presented to illustrate how to employ the model and determine the allowable expense for a candidate sensing technology by selecting the optimal maintenance trigger to achieve the minimum total cost of operations. For the purpose of this illustrative exercise, a simulation written in MATLAB, was performed to fundamentally track the changes of RR over time and the corresponding expense in line with the equations developed in the previous sections. The general logic for simulating $TC_{OpConventional}$ and $TC_{OpSensing}$ is shown in Fig. 2. The volume of work for an increment of operation time is calculated [Eq. (9)] and added to ΣV_{Work} until the maintenance threshold is reached. When the maintenance threshold is reached, the maintenance is assumed to be applied to the entire length of the haul road. The hauling operation continues on the same haul road although the production rate is lower due to assumed interference from the maintenance activity. The V_{MWork} is calculated and then accumulated with ΣV_{Work}. Once the maintenance is finished, the haul road is assumed to be restored to its initial RR level and regular (unrestricted) hauling operations start again. However, maintenance is not pursued even though the maintenance trigger is reached when the ΣV_{Work} is within 95% of TV_{Work}. It is assumed that the manager prefers at that point to complete the work without performing more maintenance. The simulation is finished when the ΣV_{Work} is equal to TV_{Work}.

A Caterpillar 730 articulated dump truck is selected as the hauler and a straight and level haul road section is assumed so the road curvature and grade have no effects on the hauling operations. The length of the haul road is assumed to be 1,000 m. The T_{Fix} is assumed to be 3.6 min and HC_{HaulOp} and $HC_{Maintennace}$ are assumed to be \$100 and \$70 per hour, respectively. TV_{work} of the project is 100,000 m^3. For simplicity, $T_{Maintenance}$ is assumed to have a step function relationship with RR, as shown in Fig. 3, capturing the concept that the effort ($T_{Maintenance}$) required to restore the initial RR level from a higher RR level is greater than that for a lower RR level.

Simulating Total Cost with Sensing ($TC_{OpSensing}$)

Once the RR profile is available through the adoption of sensing technology, the optimal maintenance trigger and minimal total cost can be obtained accordingly. Because of the lack of this information in current practice, data obtained from related research is modified to give a rough understanding of how fast the unpaved road might deteriorate.

Jones et al. (1984) established regression relationships between rut depth and traffic (passes on the roads) on the deterioration of unpaved public roads of four different soil types. Although the deterioration rates of the soils are different, the deterioration trend resembles the reverse of the typical trend of increasing density resulting from successive passes of compaction equipment (Townsend 1959; Nunnally 2000). From data reported by Jones et al. (1984), the final portion of the curve, for a lateritic gravel surface type, shows that the rut depth of the road surface plateaus. Their deterioration curve for rut depth of lateritic gravel under accumulated traffic was selected for this case illustration. To obtain a plausible RR deterioration profile from this curve, this information can be transformed by replacing the rut depth with RR [by Eq. (2)] and replacing traffic with time. The transformation shows that the RR deteriorates from 19 to 36 kg/t during the time period of 500 days if the traffic volume is 240 vehicles per day. However, the appropriate RR for a heavy hauler operating on firm soil is around 30 kg/t (Schaufelberger 1999). It is also believed that the traffic and the load will affect the deterioration rate. According to Thompson (1996), it takes about 10 days for a mine haul road to reach its worst condition. Based on these two studies, a modified regression equation is constructed and shown as Eq. (15) and this hypothetical deterministic profile of haul road RR increase with time (t) is shown in Fig. 4. The initial RR level of the selected haul road section is assumed to be 30 kg/t and is assumed to deteriorate to 60 kg/t after 80 h (8-h work days) of operations

$$RR = -0.0001329t^3 + 0.0169t^2 - 0.1329t + 30 \qquad (15)$$

The production rate during any cycle is calculated from the given RR profile, as shown in Fig. 5(a). The accumulated volume of work with time is shown in Fig. 5(b). This plot illustrates the

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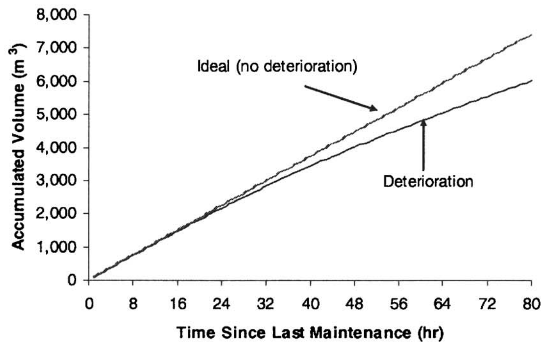

Fig. 5. Productivity profile and volume of work as a function of time

outcome of not factoring haul road deterioration into production estimates. In this example, accumulated volume of work is overestimated by about 5% if the RR deterioration effect is not considered when the T_{Op} is 32 h and by about 23% when the T_{Op} is 80 h.

The $\mathrm{TC}_{\mathrm{Op}}$ is simulated by changing RR from 31 to 50 kg/t by increments of 1 kg/t. It is assumed that a change in RR of that size is reasonable to address and could potentially be accurately measured using modern sensing technologies. The $\mathrm{TC}_{\mathrm{OpSensing}}$ is the minimum total operation cost ($111,985) which corresponds to an optimal maintenance trigger of 32 kg/t. Table 1 lists key values simulated in this example.

It is noted that the RR profile might vary in each hauling cycle. However, a deterministic RR profile is assumed here [Eq. (15)] because of the lack of data. Stochastic models for RR deterioration and then the stochastic simulation models can be developed if enough RR data is available.

Simulating Total Cost without Sensing ($TC_{OpConventional}$)

The logic of the simulation of the conventional method is the same as that of the sensor-based method, except for the determination of the maintenance trigger. The RR profile is borrowed from the sensor-based simulation, assuming that the haul road changes in RR condition for both maintenance strategies are the same. Calculations such as travel speed, average productivity, and volume of work are based on this virtual RR profile. A simulation that utilizes the probability of initiating maintenance to define the occurrence of maintenance cycles is developed for the estimation of $\mathrm{TC}_{\mathrm{OpConventional}}$. In this simulation, it is assumed that the haul road is maintained by a manager's visual inspection, with an observable RR degradation threshold equivalent to a RR value of 32 kg/t. This assumption implies that the experienced manager can identify the optimum RR level most of the time and establishes the most conservative comparison basis for this illus-

Table 1. Simulation of Sensor-Based Maintenance Approach

Cumulative time (h)	Cumulative volume of work (m^3/h)	RR (kg/t)	RR trigger (kg/t)	Note
0.0	0	30.0	32.0	
0.5	47	29.9	32.0	
1.0	93	29.9	32.0	
1.5	139	30.9	32.0	
⋮	⋮	⋮	⋮	
16.5	1,515	31.9	32.0	
17.0	1,560	32.2	32.0	
17.5	1,593			Maintenance
18.0	1,640	30.8	32.0	
⋮	⋮	⋮	⋮	
34.5	3,109	32.2	32.0	
35.0	31,86			Maintenance
35.5	3,233	29.9	32.0	
⋮	⋮	⋮	⋮	
1098.0	99,980	30.9	32.0	
1098.5	100,023	31.1	32.0	Stop
Total operation time (h)		1098.5		
Total maintenance time (h)		30.5		
Simulated total cost (U.S. dollars)		111,985		

Note: RR trigger=32 kg/t; 80-h deterioration profile.

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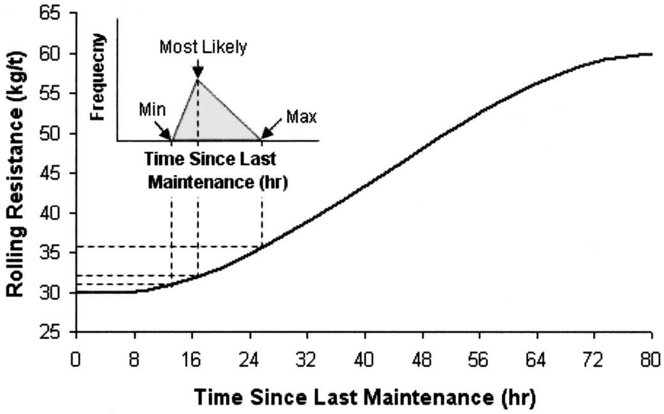

Fig. 6. Decision of distribution of maintenance frequency

tration. However, subjectivity in the timing of the manager's decision to initiate maintenance will result most of the time in the maintenance being initiated after the trigger is met, i.e., this "reactive" decision is expected to always be delayed from the time the real need for maintenance begins. From literature (Meeker and Escobar 1998), this kind of reliability data is usually modeled using distributions for positive random variables like the exponential, Weibull, gamma, and lognormal. However, a triangular distribution is adopted in this illustration because it is a simplistic description of a population, often applied when hard data is scarce and in PERT, CPM, and similar forms of project management tools (Brighton Webs 2004). This hypothetical distribution for maintenance timing frequency (time since last maintenance) is shown in Fig. 6. For the sake of this illustration, the RR corresponding to the most likely maintenance timing under the manager's inspection for equivalent RR is assumed to be 33 kg/t. The minimum and maximum maintenance timings correspond to assumed values of 31 and 36 kg/t. That is, the distribution is skew to the right and minimum, most likely, and maximum maintenance initiation timings that form the triangular distribution are 13.5, 17, and 26.5 h, respectively.

A random operation "time-since-last-maintenance" is selected from this triangular distribution and regarded as the maintenance trigger for the simulation that follows the logic shown in Fig. 2. Once the time-since-last-maintenance is greater than the randomly selected maintenance trigger (in hours), the maintenance starts. Table 2 is a listing of key variables from a single simulation of this example. After 100 trials of the simulation, the average of $TC_{OpConventional}$ is \$114,882 and the standard deviation is only \$39.

Cost Savings and Sensitivity Analysis

The cost savings is the difference between $TC_{OpConventional}$ and $TC_{OpSensing}$, which is about 2.5% (\$2,897) of $TC_{OpConventional}$ when the deterioration time is 80 h. This cost savings is simulated based on a single haul vehicle that is assumed to be equipped with RR sensing capability. Of course, any other haulers moving on the same haul road will also receive the benefits from the system. In the given scenario and under the stated assumptions, S_{RR} is the cost allowance for the adoption of a sensing system for real-time RR monitoring if only one truck is operated on the haul road. The cost savings estimate may be multiplied to account for additional haul units of the same type that might benefit from the sensing system.

As mentioned, the deterioration rates of haul roads vary with soil type. In order to show how the deterioration time affects the cost savings, two more scenarios are simulated by changing the deterioration time from 80 to 40 and 16 h, respectively. All of these results are shown in Fig. 7. It can be seen that both $TC_{OpSensing}$ and $TC_{OpConventional}$ will increase if the haul road dete-

Table 2. Simulation of Conventional Maintenance Approach

Cumulative time (h)	Cumulative volume of work (m^3/h)	Time since last maintenance (h)	Maintenance trigger (h)	Note
0.0	0	0.0	0.0	
0.5	47	0.5	18.4	
1.0	93	1.0	31.2	
1.5	139	1.5	16.7	
⋮	⋮	⋮	⋮	
20.0	1,797	19.0	18.5	
20.5	1,831			Maintenance
21.0	1,865			Maintenance
21.5	1,900	0.5	17.9	
⋮	⋮	⋮	⋮	
41.5	3,680	19.5	15.5	
42.0	3,713			Maintenance
42.5	3,707			Maintenance
43.0	3,746	0.5	16.5	
⋮	⋮	⋮	⋮	
1069.5	100,017	6.0	22.6	Stop
Total operation time (h)		1069.5		
Total maintenance time (h)		110		
Simulated total cost (U.S. dollars)		114,650		

Note: Single trial; 80-h deterioration profile.

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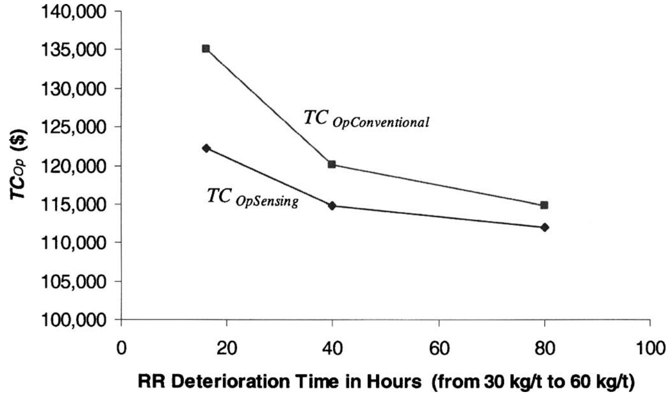

Fig. 7. Total cost with different haul road deterioration rates

riorates more rapidly. This is reasonable because more maintenance cycles are required due to a higher deterioration rate. It is also important to note that both the $TC_{OpConventional}$ and the amount by which it exceeds $TC_{OpSensing}$ increases more dramatically when the haul road deterioration rate is higher as in this illustration. The result is intuitive because if the haul road deteriorates slowly, the benefits of the sensing technology that provide the real-time data for managers occur less frequently, since there are fewer instances in which to measure the RR in real time.

Conclusions

In this paper, the writers present a model to assess the economics of options for construction equipment automation for real-time monitoring of rolling resistance and illustrate its application to a hypothetical case. Examination of the hypothetical case links the construction methods and equipment performance characteristics to the expense that can be justified by a construction contractor and highlights technology development opportunities for the equipment manufacturer. The motivation of the study is to establish a strong argument for technology development and adoption considering the characteristics of the collected data and technology benefit and cost before pursuing often more costly development of the technology option(s).

Future Work

This model has been presented in its basic form, and therefore, it should be validated through a broader range of input data and assumptions. Among other items, more examples of specific haul unit and haul road characteristics should be explored. Field data should also be obtained to validate modeling of the change in rolling resistance over time. A stochastic model for RR deterioration can be developed to present the dynamic changes in rolling resistance. From this effort, a robust model should emerge which may then be used to assess the economic attractiveness of sensing solutions for monitoring rolling resistance. A successful model validation should be followed by an experimental program which focuses on developing a low-cost, real-time, automatic method for measuring or monitoring changes in RR that has the potential for field deployment on heavy equipment used in off-road construction environments. In this process, even more will be learned about the nature of changes in rolling resistance under various conditions. The ultimate goal of this type of effort should be to identify the sensing scheme and observable parameter set that best correlates to determinations of RR or changes in RR otherwise made using traditionally accepted, yet unproven, techniques.

Notation

The following symbols are used in this paper:

Cap_{Haul} = capacity of the haul unit;
D = distance;
$E\%$ = mechanical efficiency of the haul vehicle drive train;
$E_{ff}\%$ = operational efficiency;
HC_{HaulOp} = hourly haul operation cost;
$HC_{Maintenance}$ = hourly maintenance cost;
HP = horsepower of the haul vehicle engine;
S_{RR} = cost savings gained by using new technologies;
T_{Fix} = fixed time for hauling operations;
$T_{Maintenance}$ = maintenance time;
T_{Op} = unrestricted operation time;
TC_{Op} = total operation cost;
$TC_{OpConventional}$ = total operation cost relying upon observation or rule of thumb;
$TC_{OpSensing}$ = total operation cost resulting from use of new technologies;
$TT_{Maintenance}$ = total maintenance time;
$TT_{MaintenanceConventional}$ = total maintenance time for conventional strategy;
$TT_{MaintenanceSensing}$ = total maintenance time for sensor-based strategy;
TT_{Op} = total operation time;
$TT_{OpConventional}$ = total operation time for conventional strategy;
$TT_{OpSensing}$ = total operation time for sensor-based strategy;
TV_{Work} = total volume of work for a project;
V_{OpWork} = volume of work on unrestricted hauling operations;
V_{MWork} = volume of work during maintenance;
n = number of hauling operation cycles; and
ΣV_{Work} = accumulated volume of work.

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