Optimizing Haul Unit Size and Number Based on Loading Facility Characteristics

By Douglas D. Gransberg,[1] Member, ASCE

Abstract: Determining the optimum size and number of haul units for an earthmoving project is a task of critical importance. Past approaches fail to recognize critical characteristics of the loading facility which ultimately impact on the overall system production. Regardless of the size or number of haul units used in an earthmoving project, the hauling system's total production can never exceed the productivity of the loading facility. This paper presents an improved model for optimizing haul unit size and number based on a function of loading facility characteristics as modeled by a load growth curve. The model relies on the derivation of a cost index number (CIN) to determine the optimum size and number of haul units for the given loading facility. Detailed discussions of the impact of rounding off haul unit number are also presented to highlight the importance of this decision. The paper concludes that the use of this model provides a means to design the construction equipment fleet for a wide range of material moving projects.

INTRODUCTION

An earthmoving system's productivity is limited by the production of the loading facility (Farid and Koning 1994). In other words, regardless of the size, number, and speeds of the hauling units, the ability of the loading facility to load the haul units will determine the maximum productivity of the system. As a result, the loading facility characteristics must be carefully considered in the planning of a hauling operation. Most deterministic models do include some function, such as loading time or loader productivity, which describes the loading facility. Generally, loading time is derived by dividing the haul unit capacity by the equipment manufacturer's figure for productivity (Peurifoy 1970). This does not consider the fact that the size of the haul unit may not be an even multiple of the loader bucket capacity. For example, if a front loader with a 1.5 cu yd (1.14 m^3) bucket is loading a 10.0 cu yd (7.6 m^3) dump truck, it would require 6.67 buckets to fill the truck. Because it takes virtually the same amount of time for a loader to load two-third of a bucket as it does to load a full bucket, the theoretical productivity is not achieved. In addition, legal haul restrictions and material weight must play a part in the selection of an optimum mix of loader and hauling unit. Therefore, improvements to existing methods must be made to more adequately consider the characteristics of a loading facility as modeled by the load growth curve.

LOAD GROWTH CURVE CONSTRUCTION

The 1977 version of the *Caterpillar Performance Handbook* contains a number of load growth curves for bottom-loaded earthmovers. Field experience with this management tool has shown it to be extremely valuable in modeling actual occurrences (Peurifoy and Ledbetter 1985; Atcheson 1993). The same concept can be applied to top-loading operations. To construct a load growth curve, the unit of haul capacity is plotted against the loading time. To do so, a given loading facility's loading cycle must first be separated into its various elements. These elements are then divided into productive and nonproductive categories. The physical act of placing material into a haul unit is considered productive. Other elements such as filling the bucket, maneuvering, and movement are considered nonproductive in this application. Productive elements are plotted as sloping vertical deflections, and nonproductive elements are plotted as horizontal displacements.

Example 1: A front loader with a 1.5 cubic yard (1.14 m^3) bucket has the following cycle elements:

Move to stockpile	0.05 min
Fill bucket	0.10 min
Move to truck and maneuver to load	0.15 min
Dump loaded bucket	0.10 min
Total cycle time	0.40 min

The constructed load growth curve is shown in Fig. 1. There are a total of 0.3 min of nonproductive time and 0.1 min of productive time.

BELT CONVEYOR LOAD GROWTH CURVE

The same theory can be applied to all types of loading facilities. The load growth curve for a belt conveyor is parabolic until it reaches its top operating speed where it then becomes a straight line. Thus it has two elements of cycle time: accelerate to operating speed and operate at that speed until the haul unit is full. Both these elements are productive. This can be simplified as a straight line by decreasing the slope of the steady-state line to compensate for the initial acceleration time. The next set of examples illustrate the construction of load growth curves for a belt conveyor and a conveyor-fed discharge hopper.

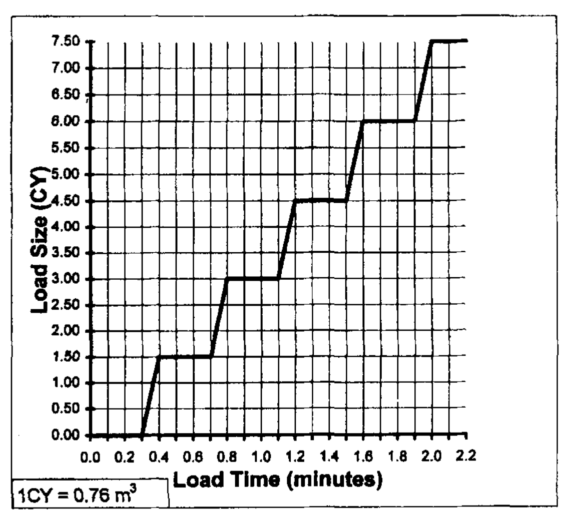

FIG. 1. Load Growth Curve for 1.5 cu yd (1.14 m^3) Bucket Loader

[1]Asst. Prof., Constr. Engrg. Technol., Texas Tech Univ., Lubbock, TX 79409-3107.

Note. Discussion open until February 1, 1997. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on September 29, 1995. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 122, No. 3, September, 1996. ©ASCE, ISSN 0733-9364/96/0003-0248-0253/ $4.00 + $.50 per page. Paper No. 11713.

J. Constr. Eng. Manage., 1996, 122(3): 248-253

Example 2: A belt conveyor has a theoretical productivity of 2,000 t/h. The time to accelerate to operating speed is 0.1 min. Construct a simplified load growth curve for this machine.

$$\text{Steady-state slope} = \frac{2{,}000 \text{ t/h}}{60 \text{ min/h}} = 3.33 \text{ t/min}$$

Assume average loading duration = 3.0 min
Therefore, percent slope reduction = 0.1/3.0 = 0.03 or 3.0%
Thus the slope for design purposes = (1.0 − 0.03) (33.33) = 32.33 t/min)

Fig. 2 is the load growth curve for this example.

Example 3: A 10.0 cu yd discharge hopper filled by a belt conveyor which is loaded by a 5 cu yd (3.8 m^3) bucket loader. The productivity of the conveyor is greater than the productivity of the loader. Therefore, as the conveyor's productivity is limited by the productivity of its loading facility (i.e., the bucket loader), its theoretical productivity is of no significance. The hopper's loading cycle can be broken into two elements: fill hopper (0.7 min) and discharge load into haul units (0.1 min). Fig. 3 is the load growth curve for this situation. It looks much like the bucket loader load growth curve shown in Fig. 1. This is because the bucket loader in this example is controlling system productivity.

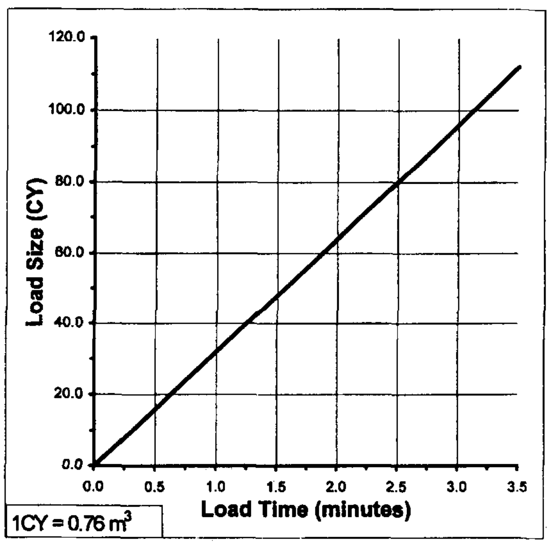

FIG. 2. Load Growth Curve for Belt Conveyor

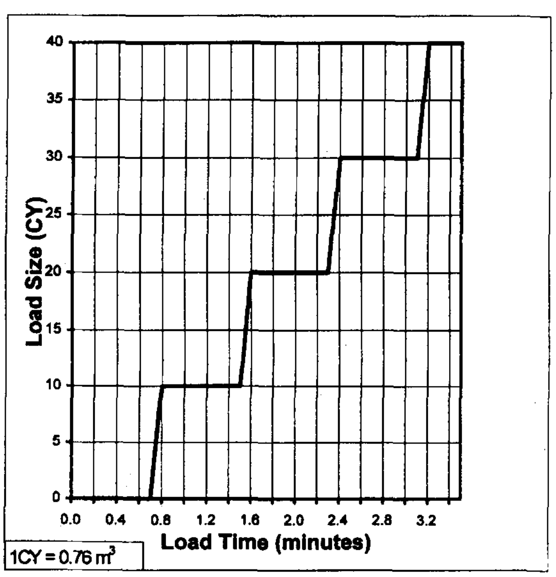

FIG. 3. Load Growth Curve for 10 cu yd (7.6 m^3) Hopper

IMPROVED OPTIMIZATION MODEL

A comparison of five deterministic, optimization methods with actual data gathered in the field found the Phelps (1977) method to be the most consistent (Gransberg 1979). Phelps takes the basic principles established by Peurifoy and Ledbetter (1985) and adds a level of realism through the calculation of sustained rather than instantaneous productivity. Phelps estimates time wasted due to human error, mechanical failure, and other unscheduled activities and allocates a portion of it to each cycle to determine the sustained cycle time and, hence, the sustained rate of production. This differs from the industry standard of using a 45–50 min "productive hour" (Atcheson 1993). Thus, the improved model takes the best characteristics from the Phelps (1977) method and combines them with load growth curve information to determine the optimum number of haul units. It also adds parameters for cost including hourly equipment ownership, maintenance and operating costs, as well as the hourly costs for labor and overhead. These costs are then related to the production system by using cost index number (CIN) analysis as the basis for optimizing. As costs vary by location, it is important to remember that the ultimate goal of optimizing a hauling system is to maximize productivity while minimizing total cost. Therefore, it is conceivable that an optimum equipment mix which is based on physical factors alone may not minimize the cost in every location. Thus, cost factors must be considered equally important to engineering fundamentals.

The analysis starts by using the Phelps (1977) method of determining maximum haul and return velocities. These velocities are then compared to the maximum allowable velocity (i.e., the legal speed limit or other restriction) to determine the actual velocities to be used to compute the variable time (V) and the travel time (T) (Phelps 1977)

$$v_H = \frac{375(\text{hp})(e)}{W_F(\text{RR} + 20(\pm S))} \quad \text{where} \quad v_H \le v_{\max} \tag{1}$$

$$v_R = \frac{375(\text{hp})(e)}{W_E(\text{RR} + 20(\pm S))} \quad \text{where} \quad v_R \le v_{\max} \tag{2}$$

$$V = \frac{60d}{v_H} + \frac{60d}{v_R}; \quad T = \frac{d}{88}\left(\frac{1}{v_H} + \frac{1}{v_R}\right) \tag{3, 4}$$

where v_H = velocity of haul direction (i.e., while loaded) (mph); v_R = velocity of return direction (i.e., while empty) (mph); $v_{\max}$ = maximum velocity based on legal speed limit or other safety restrictions (mph); hp = engine horsepower; e = engine efficiency; W_F = weight fully loaded (t); W_E = weight empty (t); RR = rolling resistance (lb/t); S = slope of haul road (%); V = variable time (min); T = travel time (min); and d = haul distance (mi).

It must be noted that (1) and (2) are limited in two cases. First, by examination, it can be seen in situations where a downhill grade (i.e., negative grade) is greater than the rolling resistance, the maximum speed is limited by characteristics of the vehicle retarder curve or operator braking to remain at a safe velocity. In addition, the actual velocity is further restricted by the legal speed limit or other factors such as the physical geometry of a superelevated horizontal curve.

The loading time (L) is then taken off the load growth curve constructed for the given loading facility. The delay time (D) along the route is estimated. These are then added to the travel time to calculate the instantaneous cycle time (C) and the optimum number of haul units (N) from the following, respectively:

J. Constr. Eng. Manage., 1996, 122(3): 248-253

$$C = L + T + D; \quad N = \frac{C}{L} \qquad (5, 6)$$

N is usually not a whole number and must therefore be rounded off. The rounding off decision is important because it will ultimately determine the maximum productivity of the hauling system. Two analytical methods are available to make this decision.

ROUNDING BASED ON PRODUCTIVITY

The decision of rounding off the optimum number of haul units up or down can have a marked effect on the system's productivity (Ringwald 1987). Rounding the number up, maximizes the loading facility productivity. Rounding the number down, maximizes haul unit productivity. Therefore, it is logical to check both and select the higher of the two. This process is best shown by example.

Example 4: A 1.5 cu yd (1.14 m^3) front loader is going to load dump trucks with a capacity of 9.0 cu yd (6.84 m^3). The loader takes 0.4 min to fill and load one bucket. The haul unit travel time in the haul is 4.0 min. Dump and delay times total 2.5 min.

$$L = \frac{9(0.4)}{1.5} = 2.4 \text{ min}$$

From (5) and (6)

$$C = 4.0 + 2.5 + 2.4 = 8.9 \text{ min}$$

and

$$N = \frac{8.9}{2.4} = 3.71 \text{ haul units}$$

Rounding down will maximize haul unit productivity. In other words, the haul units will not have to wait to be loaded, but the loader will be idle during a portion of each cycle. Therefore

$$\text{Productivity of 3 haul units} = \frac{9(3)(60)}{8.9} = 182 \text{ cu yd/h } (138.32 \text{ m}^3\text{/h})$$

Rounding up will maximize loader productivity, with the haul units having to wait for a portion of each cycle. This assumes that there will always be a truck waiting to be loaded as the loader finishes loading the previous truck. Therefore

$$\text{Loader productivity} = \frac{1.5(60)}{0.4} = 225 \text{ cu yd/h } (171 \text{ m}^3\text{/h})$$

This number can be checked by calculating the productivity of four haul units. The additional time each truck spends waiting to be loaded (A) can be calculated as follows:

$$A = N(L) - C \qquad (7)$$

In this case $A = 4(2.4) - 8.9 = 0.7$ min per cycle
Thus, actual cycle time = 8.9 + 0.7 = 9.6 min per cycle
And productivity of four haul units = 9(4)(60)/9.6 = 225 cu yd/h (171 m^3/h)

This is equal to productivity of the loader. Therefore it checks. When comparing the two possible productions it appears that it is best to round up in this case. Thus four haul units are selected. This decision also makes intuitive sense. No matter how many trucks were added to the system, they could never haul more material than the loader could load. The only way that a higher level of productivity could be achieved in this example is to add another loader or use a larger loader.

ROUNDING BASED ON PROFIT DIFFERENTIAL

Another philosophy on rounding off the optimum number of haul units involves analyzing both cases to determine which would yield the greatest amount of profit. The aim is to find the best trade-off between the added cost of an extra vehicle and the benefit of having or not having that vehicle (Ringwald 1987).

Example 5: A 1.5 cu yd (1.14 m^3) front loader has an hourly cost (H_L) of $150.00 with an operator. This figure includes jobsite fixed costs such as supervision, etc. The hourly cost of a dump truck (H_L) is $50.00 per hour with a driver. The instantaneous cycle time (C) is 8.0 min, and the loading time (L) is 1.5 min per truck. The size of the truck (S_H) is 10 cu yd. The project quantity (M) is a total of 10,000 cu yd (7,600 m^3) of material which requires hauling, and the bid unit price is $2.00 per cu yd. From (6)

$$N = \frac{8.0}{1.5} = 5.33 \text{ haul units}$$

The total cost (TC) to complete the project can be described by the following:

$$\text{TC} = \frac{M(C)(H_t(N) + H_L)}{N(S_H)(60)} \qquad (8)$$

If N is rounded down to five units, the total cost is

$$\text{TC}_5 = \frac{10{,}000(8)(50(5) + 150)}{5(10)(60)} = \$10{,}667$$

If N is rounded up to six units, the total cost is

$$\text{TC}_6 = \frac{10{,}000(9)(50(6) + 150)}{6(10)(60)} = \$11{,}250$$

The total revenue for the project = 2.00(10,000) = $20,000

Then: profit with five trucks = $9,333
profit with six trucks = $8,750

In this case it is better to round down, as greater profit is realized.

In practice, engineers tend to always round down, as it is easier to add another truck when necessary than to delete one that is not required (Gransberg 1979). The simple logic of this rule speaks for itself (Ringwald 1987). The engineer should never make this decision arbitrarily. Factors such as time, equipment, and labor constraints must be considered before the decision is made. Finally, the experience of the decision maker must ultimately be relied on to determine the most advantageous situation (Peurifoy 1975).

OPTIMIZING WITH COST INDEX NUMBER

Once the rounding off decision has been made, the total wasted time for the entire project is estimated and apportioned to each cycle to determine the waste time per cycle (W) (Phelps 1977). With this parameter, the sustained cycle time (C_s) is calculated. The sustained productivity (P_s) can also be computed.

$$C_s = C + W \text{ (if } N \text{ is rounded down)} \qquad (9a)$$

$$\text{or } C_s = C + W + A \text{ (if } N \text{ is rounded up)} \qquad (9b)$$

$$P_s = \frac{60(N)(S_H)(h)}{C_s} \qquad (10)$$

where S_H = capacity of haul unit (t or cu yd); and h shift length (h).

The total time (TT) to complete the haul of a given amount

J. Constr. Eng. Manage., 1996, 122(3): 248-253

of material (M) is a function of the sustained cycle time for one haul unit (C_s), its size (S_H), and the number of haul units in the fleet (N). In short, the total time to complete an earthmoving project is merely the total quantity of earth to be hauled divided by the production rate of the hauling system. This relationship is expressed as follows:

$$\mathrm{TT} = \frac{M(C_s)}{60(N)(S_H)} \tag{11}$$

As the object of any construction project is to make a profit, the selection of the number of hauling units should be based on minimizing the cost of haul unit production. The cost per unit of production is a function of both fixed and variable costs for a given project location. Total variable cost is directly related to the number of haul units assigned to the project and includes hourly costs of equipment ownership (EOC), hourly cost of maintenance and operation (MOC), and the hourly cost for the equipment operator (OC). EOC, MOC, and, in some cases, OC are also proportional to the size of the haul unit. Fixed costs are those costs that are independent of the size or number of haul units (IC) and include such common figures as overhead and supervision. Once the total hourly project costs are known, they can be multiplied by the TT to find the total cost to complete the project. That figure can then be divided by the total quantity of material to be moved (M) to arrive at a unit cost for a given size and number of haul units. Because other costs to complete the project are not included in this analysis, the solution is called the CIN to eliminate possible confusion with a project unit price or other financial data. The CIN is expressed as follows:

$$\mathrm{CIN} = \frac{\mathrm{TT}(N(\mathrm{EOC} + \mathrm{MOC} + \mathrm{OC}) + \mathrm{IC})}{M} \tag{12}$$

where TT = total time to complete haul (h); S_H = size of haul unit (t or cu yd); M = amount of material (t or cu yd to match S_H); N = optimum number of haul units; CIN = cost index number (dollar/t or cu yd); EOC = equipment ownership cost (dollar/h); MOC = maintenance and operating cost (dollar/h); OC = operator cost (dollar/h); and IC = size-independent costs (dollar/h).

Selecting Optimum Haul Unit Size

In most situations, a construction contractor will not be constrained to the size of haul unit that must be used prior to bidding on a project (Gates and Scarpa 1975). In many cases, trucks will be rented for the duration of the project either directly or via a subcontract. Therefore, it is very important to select the equipment mix which best satisfies the physical constraints of the actual project environment (Peurifoy and Ledbetter 1985). The foregoing model can be used to do just that. The process is illustrated by the following example.

Example 6: The front loader from example 4 with a bucket size of 1.5 cu yd (1.14 m^3) will be used to load material from a stockpile. Its load growth curve is shown in Fig. 1. 10,000 cu yd (7,600 m^3) of materials are to be hauled to complete this project. Three sizes of haul units are available to the project manager. Their details are shown in Table 1. Projects costs which are independent of haul unit size selection are estimated to be \$300/h. The material must be hauled over a haul road which has a one way length of 5,000 ft (1,500 m), 60 lb/t (3%) rolling resistance, and an average slope of +2.0% in the haul direction. The unit weight of the material is 3,000 lb/cu yd (1,776 kg/m^3). The speed limit of the haul road is 35 mph (56 km/h), and the cost for a truck driver is \$15/h. From (1) and (2) for haul unit A

$$v_H = \frac{375(109)(0.8)}{17.7(60 + 20(+2))} = 18.47 \text{ mph (29.6 km/h)}$$

TABLE 1. Specifications for Haul Units in Example 6

Item (1)	Haul unit A (2)	Haul unit B (3)	Haul unit C (4)
Capacity (cu yd)	6–8	12–14	15–17
Horsepower (hp)	109	260	260
Efficiency	0.80	0.80	0.80
Weight empty (t)	8.7	18.4	18.7
Weight full (t)	17.7	36.4	41.2
EOC (dollar/h)	8.96	11.18	13.52
MOC (dollar/h)	6.04	6.20	7.94
Labor (dollar/h)	15.00	15.00	15.00

Note: 1 cu yd = 0.76 m^3; 1 ton = 909.09 kg.

and $$v_R = \frac{375(109)(0.8)}{8.7(60 + 20(-2))} = 187.93 \text{ mph (300.7 km/h)}$$

Then comparing v_{max} = 35 mph (56 km/h)

$$v_H = 18 \text{ mph (28.8 km/h)}$$

v_R = 35 mph (56 km/h) as 187.93 mph (300.7 km/h)

is greater than 35 mph (56 km/h)

From (4)

$$T = \frac{5{,}000}{88}\left(\frac{1}{18} + \frac{1}{35}\right) = 4.78 \text{ min; use 4.8 min}$$

From Fig. 1: Entering the load growth curve on the y-axis at 6.0 cu yd (4.56 m^3), the loading time (L) for haul unit A is found to be 1.6 min. The delay times are estimated as follows (Phelps 1977):

Accelerate after load:	0.3 min/cycle
Decelerate to dump:	0.2 min/cycle
Maneuver and dump:	1.0 min/cycle
Accelerate empty:	0.2 min/cycle
Decelerate:	0.2 min/cycle
Total:	1.9 min/cycle, therefore: D = 1.9 min

Then from (5)

$$C = 1.6 + 4.8 + 1.9 = 8.3 \text{ min}$$

From (6)

$$N = \frac{8.3}{1.6} = 5.19 \text{ units}$$

As the maximum achievable system productivity is the productivity of the loader, this number will be rounded up to six units. Thus each truck will have an additional time waiting to load each cycle. From (7)

$$A = 6(1.6) - 8.3 = 1.3 \text{ min}$$

and waste time per cycle (W) is estimated to be 2.0 min.

Therefore, from (9b)

$$C_s = 8.3 + 1.3 + 2.0 = 11.6 \text{ min per cycle}$$

From (11) and (12), respectively:

$$\mathrm{TT} = \frac{10{,}000(11.6)}{60(6)(6)} = 53.7 \text{ hours of hauling}$$

and

$$\mathrm{CIN} = \frac{53.7((8.96 + 6.04 + 15)(6) + 300)}{10{,}000} = 2.58$$

The foregoing calculations can be repeated for haul units B and C to determine the optimum number (N) and the cost

J. Constr. Eng. Manage., 1996, 122(3): 248-253

TABLE 2. Cost Index Numbers for Example 6

Haul unit (1)	Optimum number (*N*) (2)	Cost index number (CIN) (3)
A	6	2.58
A with sideboards	5	2.40
B	3	2.13
B with sideboards	3	2.09
C	3	2.12
C with sideboards	2	2.47

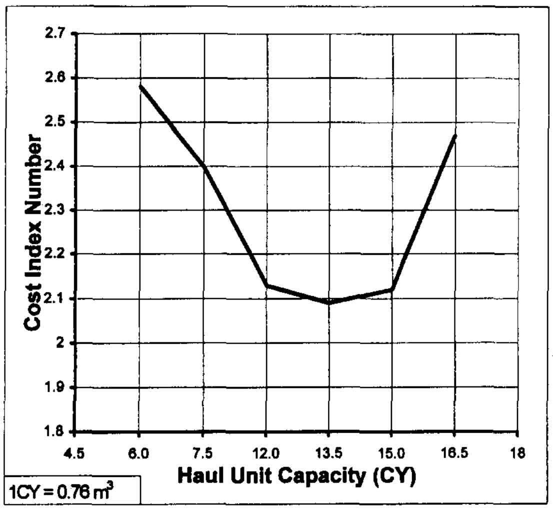

FIG. 4. Cost Index Number Curve

index number for those haul units. Assuming that the addition of sideboards would allow one more bucket of material to be loaded per cycle, a second series of calculations can be made for each haul unit with sideboards. The results of all the computations are shown in Table 2. Plotting CIN versus size in cubic yards yields Fig. 4. This shows that the use of three type B [12 cu yd (9.12 m^3) basic size] with sideboards provides the minimum CIN, and, therefore, this is the optimum size and number of hauling units for this project.

SELECTING OPTIMUM SIZE LOADING FACILITY

All the discussion to this point has centered on selecting the optimum size and number of haul units given a particular loading facility. There are times when just the opposite decision must be made (Farid and Koning 1994). The previous model can be adapted to pick the optimum size loading facility when the size and maximum number of haul units are fixed.

Example 7: Using the project information from example 6, a project manager has 10 type C haul units available and a choice of three bucket loaders to rent. The characteristics of each loader is shown in Table 3. The load growth curve for loader I is shown in Fig. 1. Corresponding load growth curves would be constructed for loaders II and III. It is poor practice to load less than a full bucket. Therefore, each loader should be analyzed loading the given haul unit with all feasible combinations of full buckets. In other words, loader I can load the type C haul unit with either 10 full buckets [15 cu yd (11.4 m^3)] or 11 full buckets [16.5 cu yd (12.5 m^3)]. The results of the calculations are shown as follows:

Loader I:	15.0 cu yd (11.4 m^3) load; $N = 2$ and CIN = 2.18
	16.5 cu yd (12.5 m^3) load; $N = 2$ and CIN = 2.09
Loader II:	16.0 cu yd (12.2 m^3) load; $N = 2$ and CIN = 2.00
Loader III:	15.0 cu yd (11.4 m^3) load; $N = 3$ and CIN = 1.48

From these calculations, loader III with the 2.5 cu yd (1.9 m^3) bucket should be chosen. It should load six full buckets [15 cu yd (11.4 m^3)] on the type C haul unit.

TABLE 3. Loader Characteristics for Example 7

Loader (1)	I (2)	II (3)	III (4)
Bucket size (cu yd)	1.5	2.0	2.5
Cycle elements	—	—	—
Move to pile (min)	0.05	0.05	0.05
Fill bucket (min)	0.10	0.13	0.17
Maneuver to load (min)	0.15	0.15	0.15
Load truck (min)	0.10	0.13	0.17
Total load time (min)	0.40	0.46	0.54
Note: 1 cu yd = 0.76 m^3.			

LIMITATIONS

The model proposed is a deterministic one and therefore shares the limitations of all deterministic models. First, the output is no better than the input. Great care should be exercised to ensure that both the physical and financial parameters used in the analysis are as accurate and as up to date as possible for the actual project location. Second, the use of sustained cycle time is an attempt to introduce a factor of realism to the model to account for variations in actual cycle times caused by human and mechanical frailty. If a factor for waste time cannot be reasonably estimated, the reader may consider using a computer simulation to establish a realistic estimate of real-world behavior (Farid and Koning 1994). Finally, the user should verify the input assumptions and variables as well as the output production rates and unit costs by actually taking field data on the project that was analyzed. Thus, adjustments can be made empirically as the project progresses.

CONCLUSIONS

The examples discussed in this paper clearly demonstrate the relative ease and objectivity with which construction equipment fleet composition decisions can be made using the salient physical parameters of a given project. The model described in this paper has three major advantages over previous models. First, its use of a load growth curve to capture the essential characteristics of the loading facility ensures that a realistic value for loading time and hence loader production is used to make haul unit selection decisions. Some previous models use a less accurate loading time function based on manufacturers' data (Atcheson 1993; Griffis 1968). Second, the model depends on sustained productivity rather than the instantaneous productions calculated in other deterministic models (Gates and Scarpa 1975; Atcheson 1993). Thus, the calculated optimum number of haul units will generally tend to be conservative, which further enhances the model's use as an estimating tool. Finally, the ultimate decision criterion is based on cost rather than some physical parameter such as time or production rate (Atcheson 1993; Griffis 1968), which leads the model's user to select a particular construction equipment fleet mix that is optimum for the financial as well as physical environment of the particular construction project.

The great danger that is faced by both project managers and estimators is the bias toward using equipment which is currently in the company's inventory without regard for potential impact on project productivity (Peurifoy and Ledbetter 1985). As a minimum, the option of renting an optimized equipment spread should be evaluated against using current equipment. In this analysis, the cost of idle equipment should be factored into the final result to allow management to select the lowest cost solution (Peurifoy 1975).

Rounding off is another decision which was shown to be

J. Constr. Eng. Manage., 1996, 122(3): 248-253

very important. One option not analyzed in this paper is to round the number of haul units up and use one of the units as a standby vehicle (Ringwald 1987). In other words, if the optimum number of haul units was rounded up from five to six, five of the trucks would be put into production with drivers and the sixth vehicle would be brought on-site for use if a production vehicle were to break down. The broken unit would then become the standby unit once repaired. Another method would be to rotate the standby unit every day and utilize the time a vehicle is out of production to perform preventive maintenance. This management technique not only maximizes equipment availability, but also reduces overall maintenance and repair costs as well-adjusted and lubricated assemblies fail at a much lower rate (Tavakoli et al. 1989). Thus a program of regular rotation of operational vehicle for on-site preventive maintenance reduces the amount of equipment time lost to unscheduled breakdowns and increases overall system productivity.

APPENDIX I. REFERENCES

Atcheson, D. B. (1993). *Earthmoving equipment production rates and costs.* Norseman Publishing Co., Venice, Fla., 6-32–6-34.

Caterpillar performance handbook. (1993). Caterpillar Tractor Co., Peoria, Ill., 8–79.

Farid, F., and Koning, T. L. (1994). "Simulation verifies queuing program for selecting loader-truck fleets." *J. Constr. Engrg. and Mgmt.*, ASCE, 120(2), 386.

Gates, M., and Scarpa, A. (1975). "Optimum size of hauling units." *J. Constr. Div.*, ASCE, 101(4), 853–860.

Gransberg, D. D. (1979). "Determining optimum size and number of hauling units," MSc thesis, Oregon State Univ., Corvallis, Oreg., 18–19.

Griffis, F. H. (1968). "Optimizing haul fleet size using queuing theory." *J. Constr. Div.*, ASCE, 94(1), 75–88.

Peurifoy, R. L. (1970). *Construction planning, equipment, and methods.* McGraw-Hill Book Co., Inc., New York, N.Y.

Peurifoy, R. L. (1975). "Cost-reducing analyses." *J. Constr. Div.*, ASCE, 101(2), 299–307.

Peurifoy, R. L., and Ledbetter, W. B. (1985). *Construction planning, equipment, and methods.* McGraw-Hill Book Co., Inc., New York, N.Y., 188–190.

Phelps, R. E. (1977). "Equipment costs." *Working Paper*, Oregon State Univ., Corvallis, Oreg.

Ringwald, R. C. (1987). "Bunching theory applied to minimize cost." *J. Constr. Engrg. and Mgmt.*, ASCE, 113(2), 321–326.

Tavakoli, A., Taye, E. D., and Erktin, M. (1989). "Equipment policy of top 400 contractors: a survey." *J. Constr. Engrg. and Mgmt.*, ASCE, 115(2), 317–329.

APPENDIX II. NOTATION

The following symbols are used in this paper:

A = additional time each truck spends waiting to be loaded (min);
C = instantaneous cycle time (min);
C_s = sustained cycle time (min);
D = estimated delay time (min);
d = haul distance (mi);
e = engine efficiency;
H_L = loader hourly cost (dollar/h);
H_t = dump truck hourly cost (dollar/h);
L = loading time (min);
M = amount of material (t or cu yd to match S_H);
N = optimum number of haul units;
P_s = sustained productivity (t or cu yd/h);
S = slope of haul road (%);
S_H = size of haul unit (t or cu yd);
T = travel time (min);
V = variable time (min);
v_H = velocity of haul direction (i.e., while loaded) (mi/h);
$v_{\max}$ = maximum velocity based on legal speed limit or other safety restrictions (mi/h);
v_R = velocity of return direction (i.e., while empty) (mi/h);
W = waste time per cycle (min);
W_E = weight empty (t); and
W_F = weight fully loaded (t).

Subscripts

E = empty;
F = fully loaded;
H = haul unit (size) or haul direction (velocity);
L = loader;
R = return direction;
S = sustained; and
t = truck.

J. Constr. Eng. Manage., 1996, 122(3): 248-253