THE COST RELATIONSHIP BETWEEN PERFORMANCE ENGINEERING AND HUMAN BEHAVIOR

G. T. Lineberry
W. J. Wiehagen

A Paradigm Shift

As market economists, mine managers are interested in "staying in business" and even "prospering." Bottom-line results are the "order of the day." Concern for bottom-line results invokes questions such as: How much was produced? At what cost? And, was anyone injured? While these questions will always carry everyday emphasis at the mine, they are fundamentally lacking in that they often appear, especially to lower levels of management and to the production worker, as preeminent concerns.

Driven by market economics, many organizations have decentralized, outsourced, downsized, restructured, and formed new coalitions. Investments in new technology and concentration on productivity have been part and parcel with these changes, contributing to improvements in both safety and efficiency. A reason for (and, perhaps a result of) these improvements has been the development of a highly experienced and flexible work force.

These changes in mining present an interesting opportunity to modify a few paradigms about work life in general, and perhaps a few paradigms about how we invest in the miner, in particular. Studying these issues now might offer some interesting opportunities for the future, as the foundations for the next generation of mine workers are laid. With the average "experienced" U.S. miner five to fifteen years from retirement, perhaps a key determinant of future success in the world market might be how well we make the transition from today's work force to the work force of tomorrow. We can ill afford to wait a few more years to tap into the special knowledge residing within a veteran mining work force. The WCPM (Work Crew Performance Model, see pp.) is one approach to defining, capturing, and transferring this expertise.

The WCPM suggests a paradigm shift, moving from a focus on products (quantity) to a focus on the process (quality). It also involves a slight change in the process--a different way to think and work. Of great importance, it entails: a belief and a commitment to people within the organization; a commitment to collect simple, but interesting, data; exploration for insightful ways to plot and integrate that data; and finally the search for creative methods to reinvest that knowledge back into the organization, that is, back into the work force.

As a way of thinking, the WCPM subordinates information about *how much* is produced daily or *how many* were injured over a year's time to concern and detail for *how the individual's and the work crew's performance contribute toward meeting organizational goals*. Drawing upon the expertise within members of that work crew to address and solve operational problems is one approach for meeting organizational goals. This everday focus on *how we work* is hypothesized by the WCPM to make the difference between a good section supervisor and the average one; an exemplar continuous miner operator and the run-of-the-mill one; a mining crew that produces consistently high quantities, but, inadvertently, degrades the production of other units. The WCPM permits objective and reliable performance data to be collected. This data then can be used: to define variability within tasks of work crew members; to relate observed variability to a cost consequence; and to more meaningfully analyze performance through the integration of traditional analytical tools, such as the production simulator, CONSIM, with a recommended behavioral approach, the WCPM.

Basis for Engineering Test

Most equipment selections and purchases involve a field trial, a test of the system. Technology is routinely bench tested at the manufacturer's facility, government agencies, and the mine site. The WCPM suggests a similar, but more practical, method for testing the performance of a work system--a test for how technology is used (by people) at the work site. It implies learning from veteran mining personnel that have gone well "beyond the book." This approach to learning and to integrating training with everyday work life can help answer such questions as: What constitutes desirable performance as a shuttle car operator, a miner operator, or a dozer operator? What characterizes exemplary performance within the context of the work system, the technology, and the work crew? How can investments in the worker be linked to measurable results within the organization? This paper explores these questions and makes recommendations for enhancing the cost linkages between investments in people and the mine's monthly cost sheets.

Use of CONSIM

The use of CONSIM, a discrete, event-oriented simulation program for analyzing face operations in continuous mining systems (Topuz, et al, 1989), offers a unique and interesting engineering test of the WCPM. The rigor of CONSIM, a standard computational tool in the mining industry, enables study of a complex problem that mine managers relate to on a daily basis: the problem of maximizing the return on investment--both on technology *and* people. In a traditional sense, CONSIM gives insight into the effect of changes in work place geometry, section layout, and equipment operating characteristics, on estimates of production. The authors have modified the use of CONSIM (but not the mechanics) to a more robust and richer application through integration of operator variability into the work system (Wiehagen, et al, 1994).

The test reported here summarizes an investigation into the impacts of variability of shuttle car operator performance on estimates of production. This variability was expressed in terms of measurable operating parameters inherent in the duty cycle of a continuous mining development section. This study recognized that production can be impacted by variability in such parameters as payload, load time, dump time, and tram rate, and that observable data and probability distributions for these data can be linked to operator proficiency. Unfortunately, in real life, the cost consequences resulting from production decrements caused by deviations from optimum operation frequently are subtle, of unpredictable magnitude, and can be confounded by other variables (e.g., breakdown characteristics and empirical distributions of individual cycle time elements and operation rates). This case study, however, permitted investigation into the effects that operator-influenced parameters alone can have on production.

Test Design

The major events in CONSIM include cutting and loading, hauling, roof bolting, and equipment breakdowns. Input data are relatively simple and include essentially:

- the dimensions of the section (e.g., number of headings; number of cuts in the sequence; dimensions of pillars, headings, and breakthroughs; cut depth; change out distance)
- the operational characteristics of the face equipment (e.g., length; tram rates of miner and bolter; breakdown data; empirical distributions for shuttle car payload, load rate, tram rate, and discharge rate; in-place constants).

Several of these operating parameters can be viewed as being linked to proficiency. For example, an exemplary shuttle car operator consistently will achieve near-optimum *payload*, will interact with the miner operator to maintain a high *load rate*, and will minimize *discharge time*. CONSIM permits rapid investigation into the effects of changes in these and other operating parameters on production.

Figure 1 shows the hypothetical, idealized section layout used for the analyses. Pertinent input data for the base case not conveyed in Figure 1 are as follows:

Shift production time	360 min
Coal density	0.042 st/cu ft
Continuous miner tram rate[1]	0.015 min/ft
Roof bolter tram rate	0.010 min/ft
Switch-in time per haul cycle[2]	0.15 min
Switch-out time per haul cycle[3]	0.15 min
Miner in-place constant[4]	4.0 min
Bolter in-place constant	4.0 min
Length of belt to be advanced	125 ft
Miner load rate	0.20 min/st
Shuttle car (S/C) payload	7.2 st
S/C tram rate from miner to change point	0.0030 min/ft
S/C tram rate from change point to dump	0.0028 min/ft
S/C tram rate from dump to change point	0.0027 min/ft
S/C tram rate from change point to mine	0.0026 min/ft
S/C discharge time	0.56 min
Roof bolter cycle time	32 min
Mining height	6 ft

An 8 x 8 test matrix was constructed, with payload varied from base case conditions (7.20 st) to 35% under base case (4.68 st) and discharge time varied from base case conditions (0.56 min) to 35% over base case (0.756 min), both in 5% increments. The objective was to test the effects of the changes in these operating characteristics on such measures as production rate, time to load the cut sequence, load time percentage, percentage of time waiting for a shuttle car, and st per shuttle car mile. To remove variability within sets of runs, all tram rates, payloads, and load rates were treated as constants, and no breakdowns were permitted.

Representative Test Results

Figure 2 shows the interrelationships among discharge time increase, payload

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[1] CONSIM requires input of tram rates in units of min/ft.

[2] Time required for an empty shuttle car to provide clearance for a loaded car by tramming into an entry at the change out point.

[3] Time required by the shuttle car to return to the haulage road after switch-in.

[4] Time required for any function other than production (e.g., gas check, hang brattice, check sprays, prepare miner to load).

decrement, and simulated production rate. As one would expect, production decreases with a decrease in effective payload. At the base case conditions, for example, the simulated production is 2.61 st/min; at a 35% payload reduction, the simulated production is 2.30 st/min. This represents an 11.9% production decrement. Interestingly, simulated production actually increases slightly (and nonsignificantly) with a 5% reduction in payload from base case conditions (7.20 to 6.84 st) before predictably decreasing as payload is incrementally reduced between runs. This occurs because of the complex interactions among load time, payload, and tram rates at these near-optimum payloads, which are best analyzed by mathematical simulation.[5] A further potential complication is the variability in clean-up car payload in each of the 77 cuts of the sequence between successive sets of runs.

Figure 2 also shows that a 35% increase in discharge time over the base case conditions results in only a 0.55% production decrement (compared to an 11.9% decrement for a simulated 35% payload reduction, as discussed above). These results suggest that maintaining a good payload is much more important than minimizing dump time, a premise that is driving a recent research emphasis into possible production gains through chemical treatment of shuttle car payloads during continuous mining operation (Leonard, et al, 1994). This example shows how production analyses can be used to rank candidate subtasks for performance improvement attempts and to help carry out cost-benefit analyses.

Figure 3 shows the effect of tram rate increase on simulated production rate. For each of the eight simulation runs, velocity on each of the four shuttle car haul components was increased in increments of 0.0001 min/ft, which, for example, amounts to an increase of 11.5 ft/min (0.131 mph) between tram rates of 0.003 min/ft and 0.0029 min/ft. An increase

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[5] For payloads above about 7 st, there were no further significant production gains, even if it can be assumed that discharge time can be held constant (Wiehagen, et al, p. 32).

in tram rate of 0.0007 min/ft in each of the four haul segments (0.0023 from 0.003, 0.0021 from 0.0028, 0.002 from 0.0027, 0.0019 from 0.0026 (see previous input data), amounting to increases above base case of 23.3%, 25%, 25.9%, and 26.9%, respectively) results in only a maximum 0.136% increase in simulated production rate, or 0.036 st/min. In one shift (assuming 360 min of production time), this totals about 13 deferred tons. These 13 st/shift are significant, as it represents the existing paradigm of "working faster." However, it is not the *only* solution set. Another solution might imply that the cost consequences of accidents and downtime as a result of overspeed on haul roads, at least in this example, could exceed the economic benefit of increasing tram speed over base case conditions. In this case, a simulated tram rate increase of approximately 25% over base case velocities resulted in a simulated production increase equivalent to less than two additional shuttle car loads per shift. An alternative interpretation of the CONSIM results suggests that reducing the variability in mining system downtime (e.g., cable damage, canopy and undercarriage damage) could more than offset the deferred 13 tons of production (all of which were obtained in the simulation by simply "running faster").

In 1991, 331 accidents involving shuttle car operation in U. S. underground coal mines were reported to MSHA. Of this number, 297 (89.7%) were classified in the "powered haulage" category. In an analysis of 267 of these 297 shuttle car accidents[6], "operating at a speed too great for existing conditions" was the inferable primary causal factor in 161 (60.3%). These 161 accidents resulted in a total of 8416 days lost and a reported total cost

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[6] Data were omitted for 30 reported accidents for which no narrative was available. The balance was sorted by two researchers, with consensus reached regarding the role that excessive speed had on accident causation.

of $ 1.25 M. Applying the 1:10:30:600 accident ratio[7] (Bird, 1980), coupled with the potential for equipment damage, accelerated equipment degradation, and compromise of structural integrity (knocked out roadway timbers, broken bolts, reduced pillar size due to rib rubbing or glancing blows), it is likely that the cost consequences of operating at unsafe speeds far exceed this reported total. Attention to these many sources of negative cost consequences offers the potential for providing a much larger basis for more effective control of total incident losses than the problematic dependent measure of injury data alone.

Summary

Use of a face production simulator, such as CONSIM, in conjunction with an empirically-based method for successively improving work crew performance, such as the WCPM, can help identify and rank cycle elements for implementation of intervention strategies. This, in turn, can help human resource developers better target groups of tasks and subtasks as candidates for improved training or coaching, for job/equipment/condition modification, or for changes in management practices/policies. The net result is the acquisition of an ability to offer more specific guidelines for human resource development at the mine site-- guidelines that are based on empirical evidence and meaningful analysis of performance metrics. Even pure "market economists," tempted always to seek technology and human operators that "run faster" at "less cost," might now consider investments that empower workers to "run smarter."

Moreover, use of CONSIM has shown, by example, how common operating parameters (e.g., payload, tram rate) can be used as cost-conscious indicators of performance variability and therefore targeted for performance improvement. This field trial of the WCPM affirms

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[7] *Major injuries* (death, disability, lost time, or medical treatment): *minor injuries* (first-aid): *property damage accidents: incidents with no apparent injury or property damage.*

the congruency between production and operator training by providing a unique cost linkage between performance engineering and human behavior.

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References

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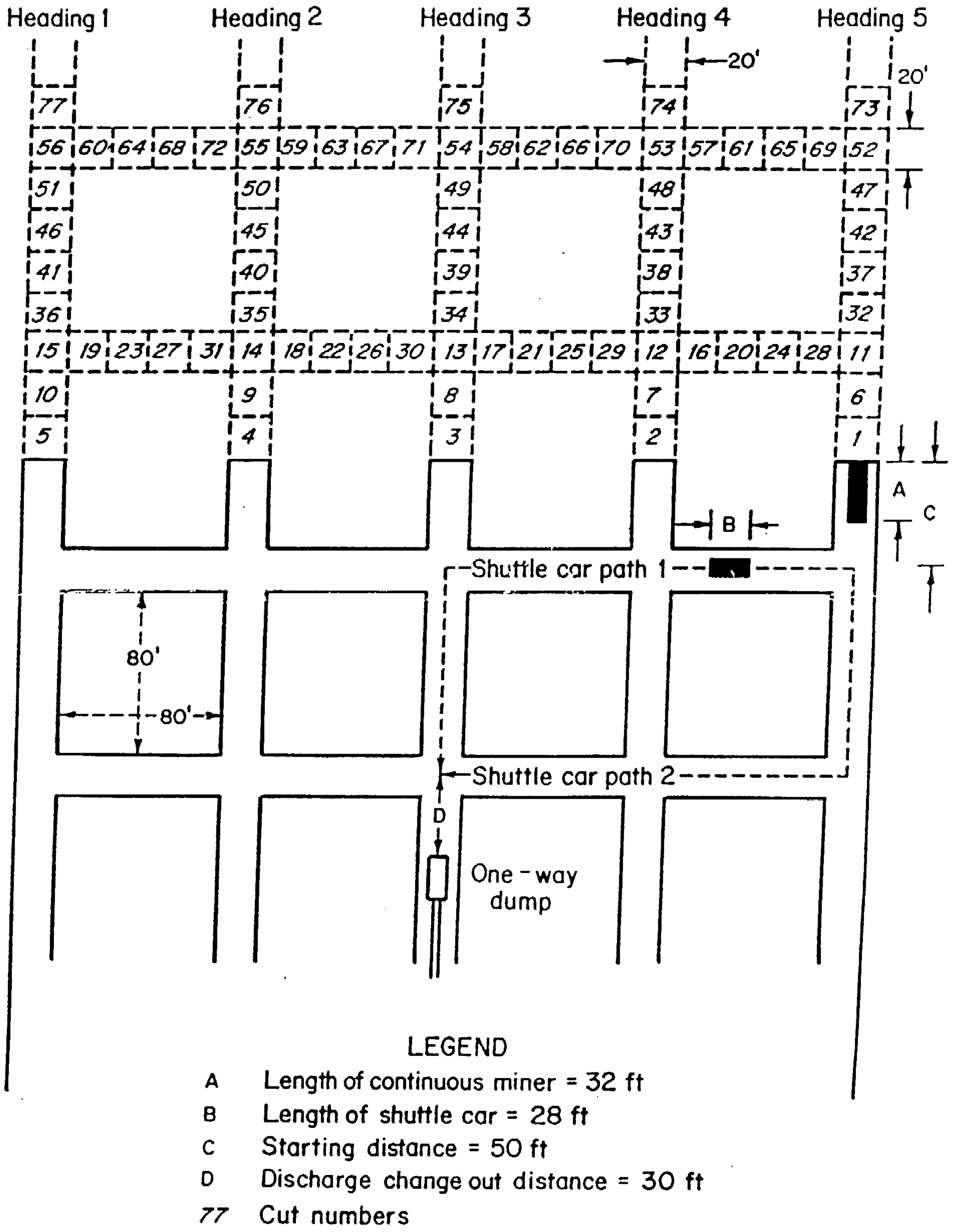
Conversions

1 ft = 0.3048 m
1 cu ft = 0.02832 cu m
1 mph = 0.447 m/s
1 st = 0.9072 tonne

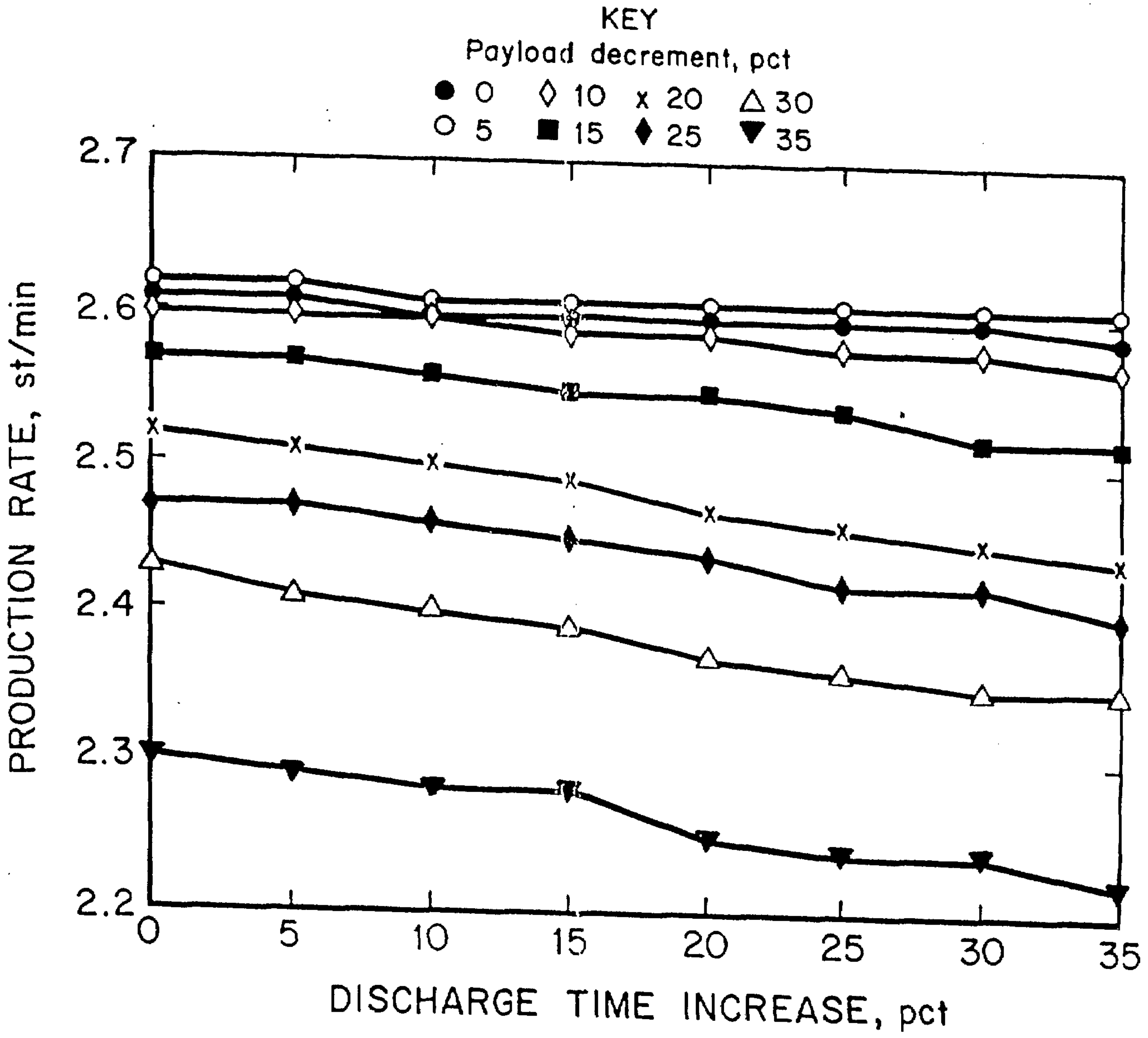
List of Figure Captions

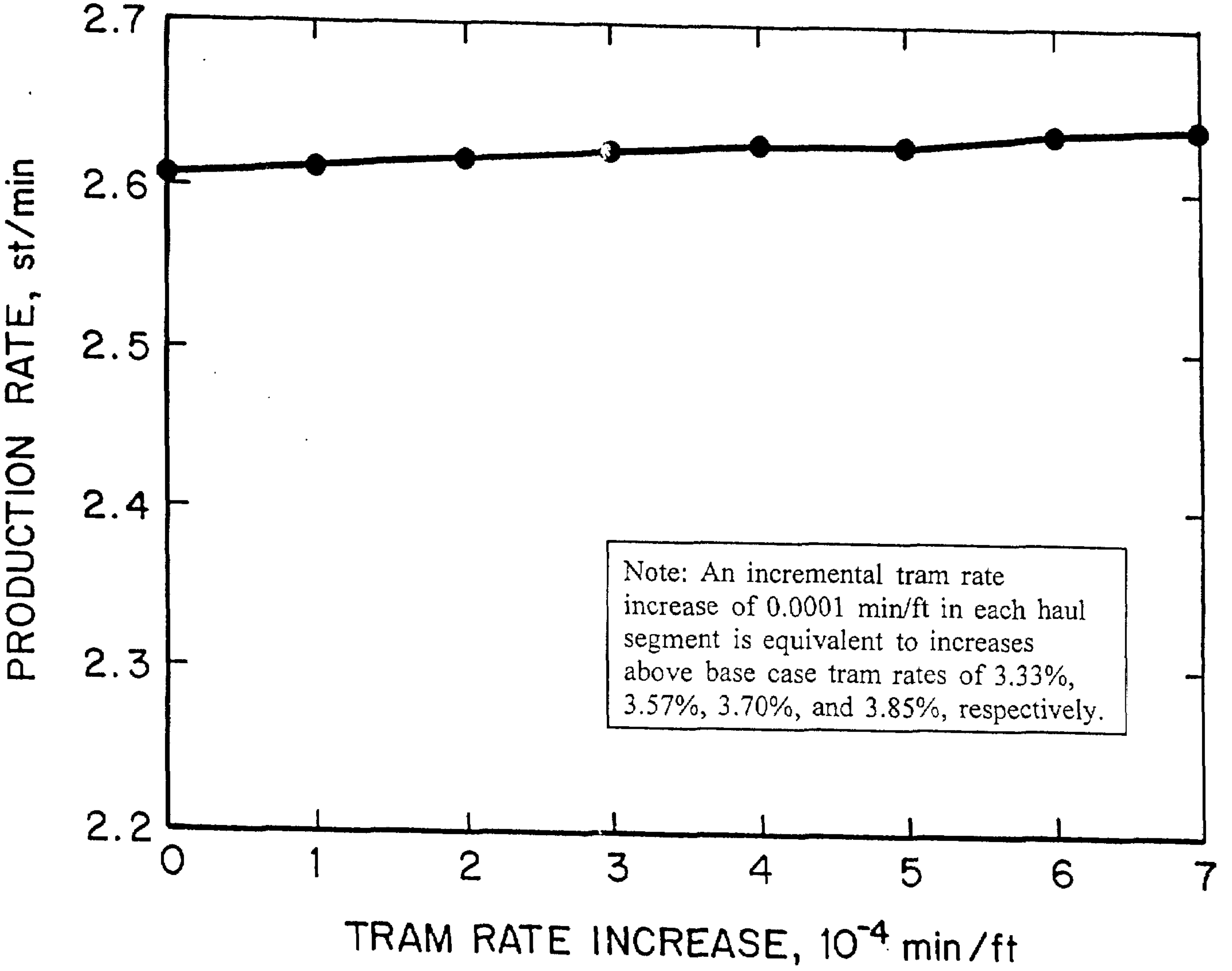
Figure 1.	Hypothetical, idealized section layout, showing cut sequencing and some system variables (After Topuz, Nasuf, and Ramachandran, p. 32).
Figure 2.	Simulation results; interrelationships among payload decrement, discharge time increase, and production rate.
Figure 3.	Simulation results; effect of tram speed increase on production rate; 7.20 st payload, 0.56 min discharge time.



LEGEND

A Length of continuous miner = 32 ft
B Length of shuttle car = 28 ft
C Starting distance = 50 ft
D Discharge change out distance = 30 ft
77 Cut numbers


KEY
Payload decrement, pct
● 0
○ 5
◊ 10
■ 15
x 20
♦ 25
△ 30
▼ 35
PRODUCTION RATE, st/min
2.7
2.6
2.5
2.4
2.3
2.2
0
5
10
15
20
25
30
35
DISCHARGE TIME INCREASE, pct



Note: An incremental tram rate increase of 0.0001 min/ft in each haul segment is equivalent to increases above base case tram rates of 3.33%, 3.57%, 3.70%, and 3.85%, respectively.