

THE USE OF TIME-LAPSE PHOTOGRAPHY AND COMPUTER SIMULATION FOR LOADER-TRUCK PRODUCTION STUDIES

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This paper illustrates how a combination of 2 relatively new analysis techniques for the construction industry—computer simulation and time-lapse photography—may be used to provide a construction estimator and planner with additional tools for determining the optimum method of earthmoving with loaders and trucks. The paper discusses the method of data collection using time-lapse photography and the production results obtained. It also discusses the development of the SIMSCRIPT computer simulation program based on the results of these field observations and indicates how a program of this type may be validated. The authors conclude that the results obtained should be helpful to contractors in their decision-making responsibilities.

•ONE of the most commonly used production systems for the earth-moving phase of a highway construction project is the loader-truck operation. This operation may be viewed as the link-node system of interdependent linked operations shown schematically in Figure 1.

Link 1 represents the loader operating in the cut area, and node 1 represents the interface activity of the loader dumping into the trucks. In a similar fashion, link 3 represents the compaction equipment at the fill and node 2 represents the interface operation between the trucks and the compaction equipment.

Two basic approaches may be taken when an estimator makes an economic comparison between alternative methods of construction for earth-moving operations of this type. The most common one (i.e., the one suggested by equipment manufacturers) views the operation as being deterministic, where single-value time durations are assigned to each component of the production cycle. A number of researchers (1, 2, 3) have felt that this approach results in inaccurate estimates, and they have suggested that a stochastic approach should be used (i.e., where an attempt is made to model the natural random variations of time for each component of the cycle).

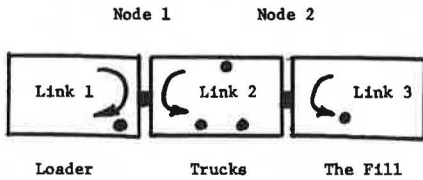
For relatively simple construction operations, the mathematical modeling approach explained by Griffis (4) may be used for a stochastic analysis. For more complicated operations (particularly when alternative methods of construction are to be evaluated), a more efficient stochastic approach involves the use of computer simulation. O'Neil (5), for example, has developed an open-mine loader-truck simulation in FORTRAN, and Gaarslev (1) has developed one in GPSS. No one as yet has attempted to develop such a simulation in the more flexible simulation language known as SIMSCRIPT.

All of these methods of computer simulation have one thing in common, however, since they all require some knowledge of the probability distributions of the various time components of the production cycle. As noted by Parker and Oglesby (6), one of the techniques that may be used for a time-study analysis of construction operations is time-lapse photography. It may be used by a contractor to determine accurate field

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Figure 1. A 3-link system, with 2 dependent nodes.



productivity and field cost information.

The principal objective of this paper is to illustrate how these 2 relatively new analysis techniques for the construction industry, computer simulation and time-lapse photography, may be used in combination to provide a contractor's cost estimator with additional tools to determine an optimum method of production. This is done by relating some of the steps taken by the writers in the research on several Pennsylvania highway construction projects. The paper is divided into the following parts:

1. A discussion of the method of data collection on loader-truck operations using time-lapse photography;
2. A discussion of the results of the time-lapse data analysis; and
3. A discussion of the SIMSCRIPT computer program that was developed based on the field observations.

COLLECTION OF FIELD DATA

The loader-truck operation on 3 highway projects being built for the Pennsylvania Department of Transportation by 3 different Pennsylvania contractors was observed to define the important elements of the operation and to collect the cycle time data required. All 3 projects employed large loaders to charge sizable off-highway trucks with blasted rock. The objective of this paper, as noted earlier, is not only to indicate the type of data that may be obtained by time-lapse photography but also to show the type of computer simulation program that would allow an estimator to consider all of the typical situations in the description of the projects when he is evaluating alternative plans for a particular project.

Description of the Projects

On Project A, 4 Euclid 70-ton (63.5-tonne) bottom-dump trucks were being loaded with a well-blasted mixture of sandstone and limestone by a Hough 400 loader with a 10-yd³ (7.65-m³) bucket. A bulldozer assisted the loader in working the face of the cut, which was 200 ft (61 m) wide. The haul road, which was 4,750 ft (1448 m) long, had downhill grades that varied up to a maximum of 8 percent and a rolling resistance that varied from 2.5 to 5.5 percent. The fill area was 250 ft (76 m) wide by 600 ft (183 m) long. The data were collected while the first lift was being placed in this fill. The original ground was of a swampy nature, so it was necessary for the bottom-dump trucks to turn and dump at the same time. This caused the trucks to spend considerably more time at the fill than was required to dump the trucks. There was one bulldozer at the fill that, in addition to maintaining the grade, assisted in extricating the trucks that became stuck.

On Project B, 3 Euclid 50-ton (45.4-tonne) rear-dump trucks were being loaded by a Michigan 475 loader with a 12-yd³ (9-m³) bucket. On the first visit (called Project B1) the material being loaded was earth loam, and on the second visit (called Project B2) the material was a very hard, not well-blasted, grey limestone. The cut was approximately 300 ft (91 m) wide, allowing ample maneuvering space for the trucks. A bulldozer was not used to assist the loader. The haul road was approximately 1,600 ft (488 m) long and was almost entirely downhill, with grades up to 24 percent and a rolling resistance of about 3.0 percent. The fill covered a large area. There was 1 bulldozer and 1 compactor working in the fill area. The trucks backed into position and dumped without the direction of a foreman or laborer on the ground. The return trip began before the box of the truck had reseated itself.

On Project C, 3 observations (called Projects C1, C2, and C3) were made over a 3-month period. The well-blasted sandstone was loaded by a Michigan 475 loader with a 12-yd³ (9-m³) bucket into the following equipment: on Project C1, 2 WABCO and 2 Euclid 50-ton (45.4-tonne) rear-dump trucks; on Project C2, 3 WABCO and 3 Euclid 50-ton (45.4-tonne) rear-dump trucks; and on Project C3, 4 Euclid 50-ton (45.4-tonne) rear-dump trucks. The cut area was approximately 150 ft (46 m) wide and 250 ft (76 m) long, and a bulldozer was pushing material to the loader at all times. On Project C1 the haul road was 2,600 ft (792 m) long and had grades that varied from 15 percent up to 14 percent down and rolling resistances from 2.5 percent to 5.0 percent. On Projects C2 and C3, the haul road was 6,300 ft (1920 m) long and had grades that varied from 3 percent up to 20 percent down and rolling resistance of about 3 percent. The fill on Projects C1 and C3 was nearly identical to the fill on Project B. The trucks backed into position, discharged the material, and pulled away a short distance. The trucks stopped at this point until the box was lowered to its "rest" position and then resumed their return trip. On Project C2, the fill operation was unique, at least with respect to the other operations observed in this study. The material was being used as backfill for a concrete box culvert 500 ft (152 m) long. There was considerable congestion in this area. The fill was located near the project office. There was traffic caused by the supervisors, mechanics, inspectors, etc., traveling through the area. The trucks dumped their loads near the culvert. Small front-end loaders were then used to transport the backfill material to the excavation; 2 compactors were also used.

Data Collection

A stopwatch is the most commonly used means of collecting component time data on construction operations. A stopwatch is an excellent means of recording sequential events involving 1 or 2 men, a man and a machine, or 2 machines. There are, however, several problems that arise in stopwatch studies:

1. There is a limit to the number of events that a single observer can record;
2. The observer must decide instantly when one cycle or event stops and another begins; and
3. The only permanent record of the observation is the notes kept by the observer.

Time-lapse photography was used in this research in an attempt to overcome these shortcomings. The basic idea behind the time-lapse method is to allow some time to elapse between the exposure of 2 consecutive frames of film. The effect is to compress the time required to observe an event. A time-lapse movie has no limitation on the number of events that may be recorded as long as they are within the field of view of the camera. The film provides a permanent record of the operation, and there is no immediate field decision required regarding the beginning or the end of events.

The time interval between frames for this study was 2 seconds. This interval, rather than a 4-second interval, was chosen because the error inherent in the cycle time calculations is reduced as this time interval is reduced. On many occasions when taking time-lapse movies, the beginning or end of a cycle will occur between frames. By decreasing the time interval between exposures, the number of these occurrences is decreased.

Two super-8-mm movie cameras manufactured by Time-lapse, Inc., of Palo Alto, California, were used so that both the loading and the dumping of the trucks could be photographed at the same time. It was felt that, if 2 cameras could be synchronized, the haul and return travel times of the trucks could be recorded by comparing the 2 films. The 2 operators of the cameras were supplied with 2-way radios so that they could be in constant communication. It was necessary for the operators to maintain communication to ensure that the cameras were started and stopped at the same time.

Colored magnetized plastic signs were fastened to the trucks. The signs were 18 in. (457 mm) square and were placed on each side of the truck so that each truck could be identified in both the loading and dumping films.

The films were analyzed by using a projector also manufactured by Time-lapse, Inc. This projector is capable of a variable speed of viewing, and it has a built-in frame counter. This made it possible to count the number of frames between events (for example, between the beginning and end of a load cycle).

Data Collection Problems

As noted, the original intent was to obtain haul and return times as well as loading and dumping cycle times directly from the synchronized films. Although the latter objective was achieved, unforeseen problems prevented the accomplishment of the former objective. These problems should be explained because other researchers may also want to apply the synchronized camera approach to construction operations.

The sales literature from Time-lapse, Inc., stated that there is a ± 2 percent maximum error in the time interval. The analysis of the processed films indicated that, although this 2 percent error did not adversely affect each film, it had a profound effect on the travel times, which required a comparison of 2 films. The error is cumulative because it depends on the duration of the component time being observed. In the case of a load cycle of 40 seconds (i.e., 20 frames if the timing interval is 2 seconds per frame), if the camera has a positive error of 2 percent, the error per cycle is 0.8 second or 0.4 frame. This means that the actual cycle time is 40.8 seconds, not 40 seconds. This error is less than the 2-second interval between frames, and therefore it was deemed insignificant.

For the travel time calculations, however, it was necessary to maintain a continuous frame count. The frame number for an event (truck arrival at the fill or truck departure at the cut) is noted for each film. The travel time was calculated by subtracting the frame number of the departure on one film from the frame number of the arrival on the other film for both the haul and return segments of the truck cycle. An event occurring at a frame count of 3,000 frames (i.e., 6,000 seconds from the start of filming) with a positive 2 percent error has an actual error of 120 seconds. If the second camera has a negative 2 percent error, then the total resultant error in the travel time components will be 4 minutes. This distortion would have resulted in an actual travel time of approximately 3 minutes being recorded as a negative quantity.

This situation was discovered after all the films had been processed and were being studied. It was felt at first that a calibration curve for each camera could be established that would allow a correction factor to be applied in order to establish the respective haul and return times. This proved to be impossible, however, because it appears that the error exhibited by a time-lapse movie camera is dependent on the charge of the battery at the time the pictures are taken. This in turn is dependent on the time interval between the end of the charging period and the beginning of the filming period, an extremely variable length of time. The conclusion drawn from this experience was that, because of the budget limitations of the research, the only reliable method of collecting truck travel times with the equipment available was by the traditional stopwatch method.

On the basis of this information, a second visit was made to one of the projects. For this visit, stopwatches were used to record the travel times of the trucks. The 2 men observing this operation stationed themselves at the cut and fill respectively, each equipped with a time-lapse camera, a 2-way radio, and a stopwatch. The cameras were synchronized. Using the radios, one observer recorded the haul time of the trucks and the other recorded the return times of the trucks. The period of observation was approximately 2 hours, during which 27 completed travel cycles were recorded.

TIME-LAPSE DATA RESULTS

This section of the paper discusses some of the results obtained when the collected time-lapse data were analyzed. The results are of interest not only because they are

an example of the type of production data that an estimator may need but also because they provide basic data about the loader-truck operation needed for the computer simulation program (as will be seen in the next section).

The loader-truck system, as is the case with many other materials-handling operations, is a cyclic operation. One method of viewing this is based on an analysis of the complete cycle of the truck. That is, the time required for the truck to arrive at the cut, be loaded, travel to the fill, dump, and return to the cut can be taken as the complete cycle time of the operation. This overall cycle time of the truck can be represented by the following equation:

$$C_t = Q_{t1} + L_t + HT + Q_{t2} + D_t + RT$$

where

- C_t is the complete cycle time of the operation;
- Q_{t1} is the queue time of a truck at the loader;
- L_t is the time required to load a truck, composed of a number of loader service times (l_t);
- HT is the haul travel time of a truck from the cut to the fill;
- Q_{t2} is the queue time of a truck at the fill;
- D_t is the time required for a truck to dump its load; and
- RT is the return travel time of a truck from the fill to the cut.

The analysis of the data resulting from the time-lapse films can determine the parameters (mean, variance, etc.) as well as the shape of the frequency distributions of each of these elements of the cycle. A discussion of some of the results obtained from the projects follows.

Time to Load Truck

The time to load a truck is actually composed of the number of individual loader service times l_t (where l_t is defined as the time required to place 1 bucketful of material into a truck) needed to fill the truck. The data collected for the loading operation were actually collected in terms of the individual loader service times because they were easier to define on the films. The basic components of the loader service times as determined from the films were

1. Forward to cut face;
2. Load bucket;
3. Back up;
4. Forward to truck;
5. Dump bucket into truck; and
6. Back up.

It was noted during the film analysis that generally 3 or 4 of these load service times were required to completely load each truck. The frequency histogram for the loader service time on Project A is shown in Figure 2. An attempt was made to determine a theoretical model that would "fit" the frequency distribution of loader service times for each project. The hypothesis that either a normal, exponential, gamma, 2-parameter Weibull, or 2-parameter log-normal distribution could be used was tested and rejected. This did not create a problem, however, because it was decided that the relative cumulative frequency distribution resulting from the data would be used directly in the computer simulation program.

The mean and variance for the loader service time for all of the projects are given in Table 1. It is interesting to note that, although the type and size of loader used and

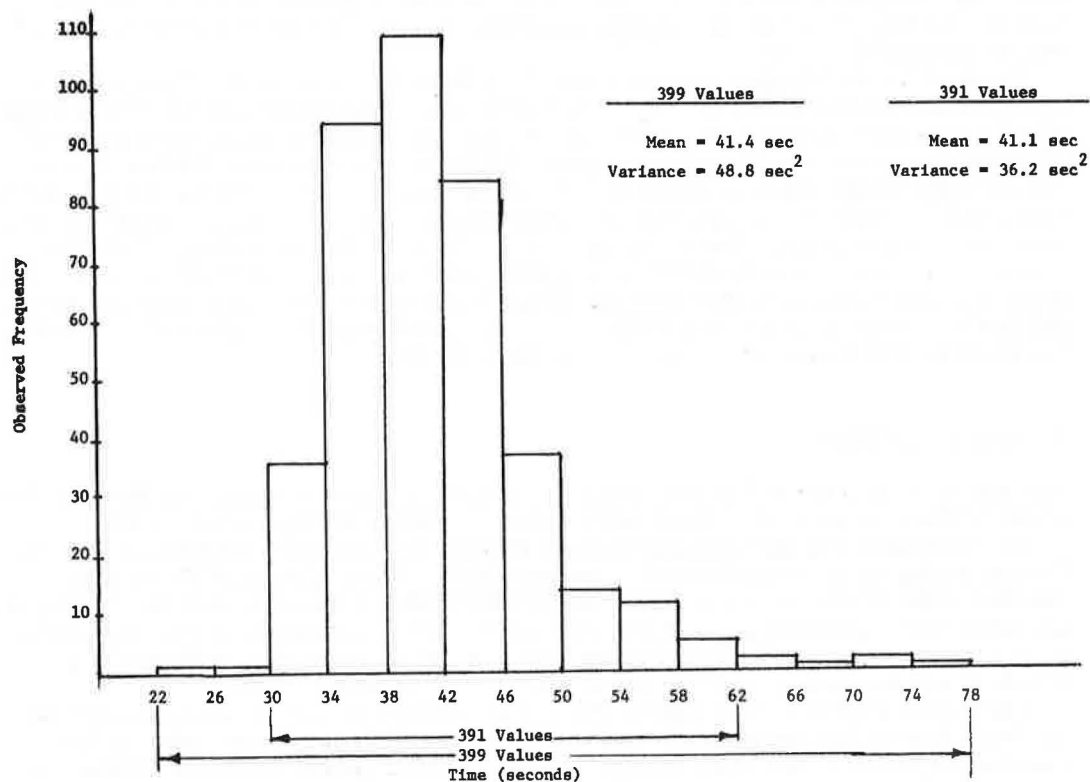
Figure 2. Histogram of loader service time (I_t) for Project A.

Table 1. Summary of load and dump cycle results for all projects.

Project	Load Service Time I_t			Dump Cycle Time D_t		
	Mean (seconds)	Variance (seconds ²)	No. of Observations	Mean (seconds)	Variance (seconds ²)	No. of Observations
A	41.1	36.2	391	42.6	129.0	71 (trucks only)
B1	38.3	27.0	165	220.3	1,397.0	71 (bulldozer)
B2	42.9	44.9	135	59.9	108.2	61
C1	38.9	32.5	119	62.7	132.2	43
C2	39.6	50.4	130	79.9	118.8	28 (WABCO)
C3	42.1	265.7	119	55.3	36.0	28 (Euclid)
				137.6	3,203.5	113
				73.7	57.7	31

the type of rock loaded varied from project to project, the average loader service time was generally close to 40 seconds. The order of magnitude of the variance (a measure of dispersion) of the frequency distribution for all projects except Project C3 was essentially the same.

Pruess (7) has indicated that truck spot time (maneuver time of the truck prior to being loaded) should be included because it accounts for approximately 15 to 20 percent of the time to load a truck. According to Pruess, this should average between 20 and 40 seconds. In the course of the collection of data for this research, the loadings of almost 1,100 trucks were observed on 3 different projects. At no time was a 40-second truck spot time observed. In most cases the truck spot time did not exceed 75 percent of the time required for 1 loader service time. As a result of this observation, the truck spot time was included in the first loader service time for each truck. The case where the truck spot time exceeded the initial loader service time and hence required the loader to wait occurred so rarely that it was considered to be sufficiently accurate to consider "truck spot time" as a part of the load cycle.

Time to Dump Truck

The definition of the time to dump a truck is slightly more conditional than the definition of the loader service time. There were 2 distinct cases observed on the films.

The first case was the situation where it was not necessary for the truck to wait for the completion of the dump time of a previous truck. The beginning of the dump time was therefore identified as the point when the truck turned from the haul path and began the maneuver time at the fill. In the case of the rear-dump trucks, it was necessary to back into the position indicated by the foreman. In the case of the bottom-dump truck, it was necessary for the truck to pull into the required position.

The second case occurred only on Project A. On this project it was necessary for the truck to wait for the completion of the dump time of the previous truck. In this case the beginning of the dump service time was defined as that point in time when the truck began moving into position to dump. In addition to the dump time of the truck, the definition of the service time of the bulldozer in the fill was also required on Project A. This is the time from the beginning of the truck dump time until the material deposited by that truck was spread on the grade. It was necessary for a second truck to wait until the bulldozer had finished spreading the material deposited by the first truck. There appeared to be 2 reasons for this truck queue time: First, clearing the area gave the trucks more room to maneuver, and second, on most of the cycles the trucks required the assistance of the bulldozer to extricate themselves from the deposited material.

There were also 2 distinct cases that occurred at the end of the dump time. When rear-dump trucks were used to transport the material (on Projects B, C1, and C2), the end of the dump time was defined as the time when the box resumed its "rest" or travel position. On Project A, where bottom-dump trucks were used, the end of the dump service time was defined as the time when the truck completed its turn to re-enter the return road.

The frequency histograms for the dump time on Project A for both the trucks and the bulldozer are shown in Figures 3 and 4 respectively. As noted for all the other projects, only a frequency histogram for trucks was determined. The statistical analysis of the dump time for the projects indicated (as had been the case for loader service times) that the standard mathematical models did not "fit" the data. As a result, a relative cumulative frequency polygon was again calculated for each dump time on each project and was used directly in the computer simulation program.

Table 1 gives the mean and variance for the dump times for all of the projects. The first thing to be noted about these results is that the variance of the data is very large in almost all cases. This indicates that, although the loader service time was fairly well-controlled (i.e., the variances were smaller), the same statement cannot be made for the dump times. This indicates the need to study seriously the dumping operation on a loader-truck operation because there appears to be a real opportunity to reduce

Figure 3. Histogram of dump time of trucks at the fill (D_t) for Project A.

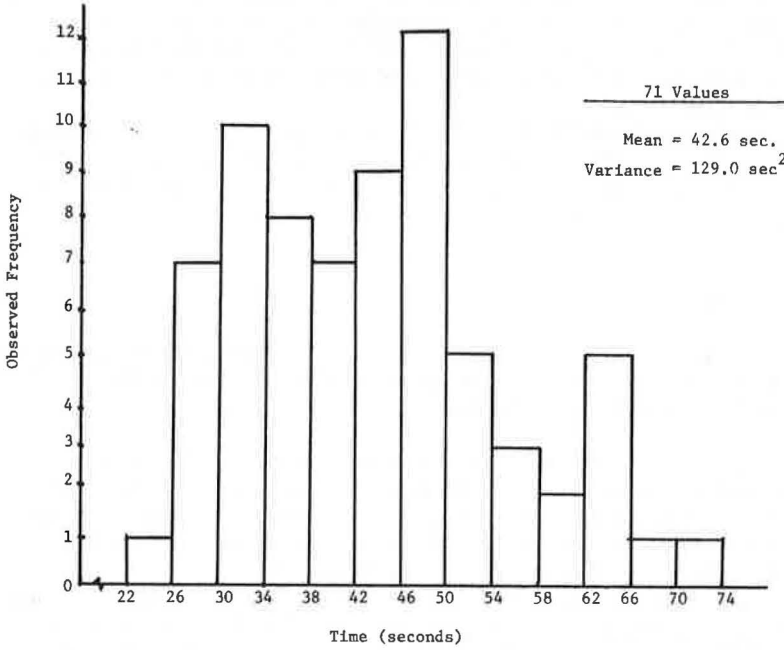
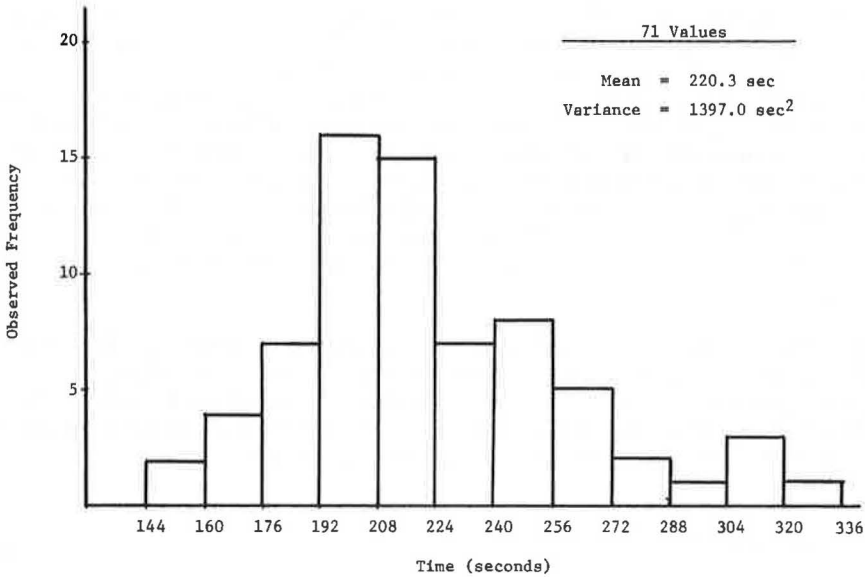


Figure 4. Histogram of dump time (governed by dozer at fill) for Project A.



the truck cycle time by modifying the practices at that location.

It is interesting to note that on Project A, which had a bulldozer affecting the operation, the dump time is much higher than on other projects. It is also interesting to note that on Project C1, when the dump times for the WABCO and Euclid trucks are studied separately, it appears that the former truck requires more time to dump and has a wider dispersion of dump times.

The final point to be made concerns the dump time for Project C2, which involved the backfilling of the box culvert. The greater length of time required and the relative confusion of the operation are clearly indicated by the fact that the average dump time is 137.6 seconds and the variance is 3,203.5 seconds².

Other Cycle Time Components

Other items of the truck cycle time were analyzed in the full research report (8) that are not discussed in detail in this paper. An attempt was made to identify the following items from the films (or related stopwatch readings):

1. Truck delays, which were defined as events that caused a truck to spend a greater amount of time on the haul or return road than the minimum observed haul or return time. In most cases a truck delay occurred out of the view of the camera. As a result, the delay times were calculated by subtracting the minimum observed haul or return time from each of the observed haul and return times.
2. Loader-caused delays, which might also be called loader breakdowns. In many cases these delays were a result of mechanical failures of the loader. In other cases, the delays were caused by outside interference—for example, a short interruption due to the drilling and shooting operation. The case of a loader cleaning up the work area was also classified as a loader-caused delay if a truck was waiting to be serviced during the cleanup work. This cleanup work usually involved removing loose rock fragments from, and maintaining a level surface in, the maneuvering area. The time between loader-caused delays was also accumulated from the time-lapse films because this information was needed in the computer simulation program.
3. Equipment wait times, which were of two types, the time the trucks spent waiting to be serviced at either the cut or the fill (truck queue time) and the time the loader spent waiting for trucks to arrive (loader idle time). The loader idle time included the time the loader spent cleaning up the cut floor if there were no trucks waiting for service. It should be noted that the only occurrence of truck queue time at the fill was on Project A. This was caused by the type of trucks being used and the nature of the dumping operation. There were no truck queue times at the fill observed on any of the other projects.

The time-lapse data results discussed in this section should indicate that the level of information that an estimator has about the loader-truck operation by using this method is clearly superior to the estimating rules of thumb he is probably using. The next section of this paper shows the use for these time component results in a computer simulation program that attempts to describe the loader-truck operation.

THE COMPUTER SIMULATION

The experiences gained by the field observations of the loader-truck operation permitted the boundaries of a typical loader-truck operation and the elements that interact within it to be defined. At this point in a production study, one of a number of computer simulation languages can be used to prepare a stochastic model of the system. This section of the paper describes the type of simulation model that may be developed in SIMSCRIPT II.5 in order to define the operation. Additional details are given elsewhere (8).

Background

The SIMSCRIPT II.5 language used in the simulation program was developed initially at the Rand Corporation in the early 1960s to advance the "simulation art" as well as to facilitate the writing of Air Force Logistics Simulators. The language requires that the world to be simulated be structured in terms of the concepts mentioned by Markowitz (9) in the following description:

The SIMSCRIPT programming system is especially designed to facilitate the writing of simulation programs. Digital simulations generally consist of a numerical description of "status" which is modified at various points in simulated time called "events." SIMSCRIPT simulations consist primarily of a collection of "event routines" written by the user describing how different kinds of events in a particular simulated world affect current status and cause future events. Status is defined in terms of various "entities," "attributes," and "sets" as specified by the user.

Computer Program Use of Time-Lapse Data

The computer program may be explained by discussing the event interactions that model the loader-truck operation. It should be noted that to use the program on a particular project certain information must be obtained from the time-lapse films taken for a similar equipment fleet used on a previous project. The data required for the loader-truck situation are given in Table 2.

It should be noted that information about truck travel times from time-lapse films of previous projects is not needed because the program has been designed so that a subprogram in FORTRAN calculates these times in a deterministic fashion. It uses information about the rolling resistance, road profile data, etc., which must be provided for the project being studied. These travel times are then modified by applying stochastic truck delay times to the values determined in the subprogram.

Event Interactions

Figure 5 shows the relationship between the 9 events that define the operation in the simulation program:

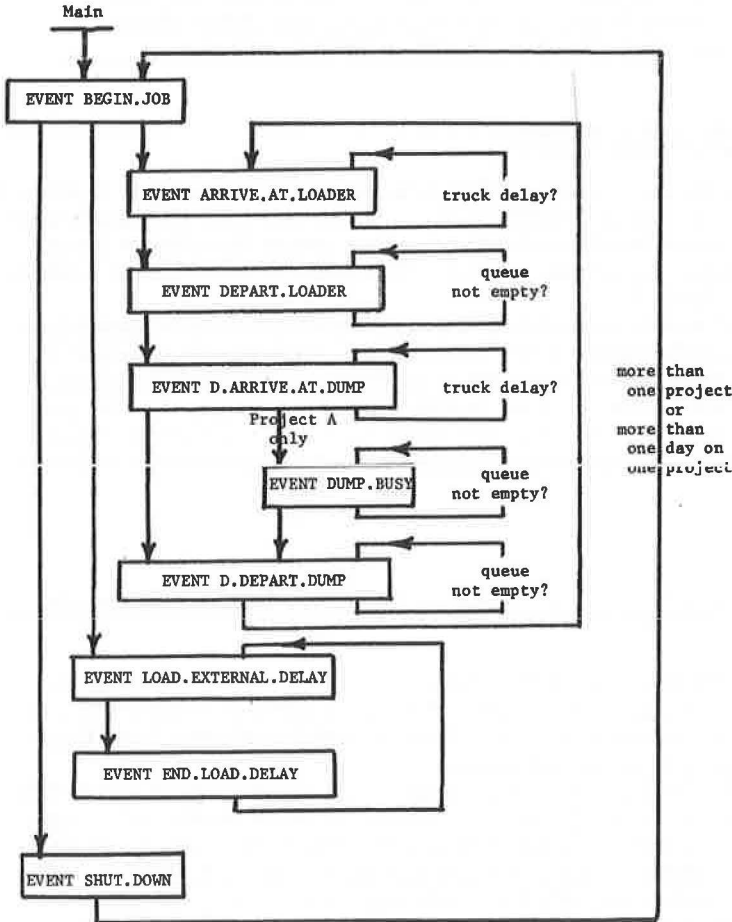
1. The event BEGIN.JOB initializes the various entities, attributes, and arrays that are required to execute the simulation based on data put into the program by the user. A loader breakdown (based on a frequency distribution determined from time-lapse data) may also be scheduled from this event.

2. The event ARRIVE.AT.LOADER makes a check to see if there was a truck delay (again generated from a cumulative frequency distribution of truck delays determined from the time-lapse films). If there is a truck delay, that truck is rescheduled to arrive at the loader. If the loader is busy, the truck is filed in the set QUEUE. If the loader is not busy, the routine R.L.SERVE schedules a DEPART.LOADER and calls the routine QUANTITY, which computes the quantity of material to be transported. [Note: The routine R.L.SERVE is used to calculate the amount of time required to load a truck, which is dependent on the service time of the loader and the number of cycles required to fill a truck. The load service time is randomly chosen from a cumulative frequency distribution of load service times determined from time-lapse film data. The routine QUANTITY computes the amount of material to be carried by a given truck on a given trip. This is done by choosing a random number from a normal distribution with a mean equal to the capacity of the loader in loose cubic yards and a standard deviation of 15 percent of the mean as suggested by Gates (10). The number of times this random number is generated depends on the number of loader cycles required to fill the truck. The quantity of material transported is accumulated as the sum of these random variables for each truck.]

Table 2. Summary of the time dependent components used in the simulation.

Component	Type of Distribution	Determination of Parameters
Load service time	Cumulative frequency polygon	Time-lapse films
Truck dump time	Cumulative frequency polygon	Time-lapse films
Bulldozer dump service time	Cumulative frequency polygon	Time-lapse films
Truck delay time	Cumulative frequency polygon	Time-lapse films
Loader delay time	Exponential	Time-lapse films
Time between loader delays	Exponential	Time-lapse films
Truck travel time		Calculated in simulation

Figure 5. Event diagram of the loader-truck model.



3. The event DEPART.LOADER checks for an empty QUEUE. If the QUEUE is not empty, the first truck in the set QUEUE is removed from the set. To simulate the loading of this truck, another DEPART.LOADER is scheduled, and the quantity of material to be transported is computed. The routine R.FILE is called to file the departing truck in the HAUL.SET. The routine H.TIME.HAUL in turn calls the routine TRAVEL.TIME to compute the arrival time of the truck at the fill. A D.ARRIVE.AT.DUMP is then scheduled. [Note: The routine TRAVEL.TIME is used to calculate the haul or return times of the trucks. This calculation is based on the rolling resistance, grade, and length of the haul (or return) road and the weight (which as stated is a random variable), rimpull, and retarder characteristics of the trucks. The haul or return road may be divided into any number of sections. Different haul and return routes may be specified.]

4. Event D.ARRIVE.AT.DUMP checks for a truck delay occurring along the haul road. If a truck delay does occur, that truck is rescheduled to arrive at the fill. If the dump site is busy, the event D.ARRIVE.AT.DUMP files the truck into the set D.QUEUE. If the dump site is not busy, the routine R.D.SERVE is called and a D.DEPART.DUMP is scheduled (to simulate a truck unloading at the dump site). If the set D.QUEUE is not empty, the event D.DEPART.DUMP calls the routine R.D.SERVE to schedule another departure from the dump site, for the first truck in D.QUEUE. The routine R.TIME.RETURN is then called, which in turn calls the routine TRAVEL.TIME to calculate the time required for the truck to return to the loader. The truck is then filed into the set RETURN.SET and an ARRIVE.AT.LOADER is then scheduled. [Note: The routine R.D.SERVE calculates the service times of the trucks at the fill from a cumulative frequency polygon determined from time-lapse data. If a DUMP.BUSY is to be scheduled, the service time of the bulldozer is computed from a cumulative frequency polygon also determined from time-lapse data.]

5. If the event DUMP.BUSY is used, the status of the dump site is set to not busy. If the set D.QUEUE is not empty, R.D.SERVE is called, and a D.DEPART.DUMP and another DUMP.BUSY are scheduled.

6. When event LOAD.EXTERNAL.DELAY occurs, the status of the loader is set to busy, and an END.LOAD.DELAY is scheduled. The length of the loader delay is a random number drawn from an exponential distribution. The mean of this distribution is supplied to the simulation as a real number in the variable MLDT, which is based on time-lapse data. If a truck is being served, R.FILE is called and a D.ARRIVE.AT.DUMP is scheduled.

7. The event END.LOAD.DELAY schedules the next LOAD.EXTERNAL.DELAY and removes the first truck from the loader queue. The time between loader delays is a random number drawn from an exponential distribution. The mean of this distribution is supplied to the simulation as a real number in the variable MLDI, and is based on time-lapse data. Routine R.L.SERVE is then called, which in turn calls routine QUANTITY and schedules a DEPART.LOADER.

8. The event SHUT.DOWN cancels any pending DEPART.LOADER events. The queue times of any trucks currently waiting to be serviced are accumulated. The status of the loader is set equal to 2, which indicates that, when all the trucks have returned to the loader, the routine CLEAN.UP is to be called. The routine CLEAN.UP calls the routine DAILY.REPORT and all the currently scheduled events are canceled. If another project is to be simulated, all the entities and their attributes are destroyed; if the same project is to be simulated for another day, the entities are saved. If the required number of days has been simulated or if the required quantity of material has been moved, the routine END.SIMULATION is called. If necessary, a BEGIN.JOB is scheduled for the start of the next day. The routine DAILY.REPORT prints out the accumulated daily statistics for the project being simulated.

Validation of Simulation Program

A very important step in the development of any simulation program is the validation stage, which attempts to determine if the predictions made by the program correctly

model reality. The procedures used to validate the program are only briefly discussed here because of space limitations. The interested reader is referred to the full report (8) for a more detailed explanation.

There are a number of parameters determined by the simulation program that may be statistically compared in the validation phase to the results determined from the time-lapse films. The first of these is the travel time of the trucks. The travel time results of the program can be compared with stopwatch readings taken at the job site while the filming was taking place. (The results from the films could be used directly if the problem of synchronization mentioned earlier could be corrected.) If the two results compare favorably, the program may be considered partially validated. Other parameters that may be treated in a similar fashion are the following:

1. The predicted versus the actual hourly production rates.
2. The frequency distribution of the predicted versus the actual truck queue times at the loader.
3. The frequency distribution of the predicted versus the actual truck queue times at the fill.
4. The frequency distribution of the predicted versus the actual loader wait times.

If it appears that these program parameters do not satisfactorily model reality, then basic changes to the assumptions in the program must be made. Once a program is successfully validated, however, the authors feel that an estimator may use the combination of time-lapse photography and the computer simulation program as valuable aids in his day-to-day activities.

SUMMARY AND CONCLUSIONS

This paper has described a procedure that combines the techniques of time-lapse photography and computer simulation to define the loader-truck operation in order to provide a construction estimator and planner with a better basis for decision-making. The method of collecting data by using time-lapse photography is discussed, and the results obtained on 3 Pennsylvania highway construction projects are presented. A SIMSCRIPT computer program that models the loader-truck operations observed is discussed.

The actual SIMSCRIPT computer program is only partially documented in the report of the project (8). A lack of research funds prevented the development of a "user's manual" for the program as well as a more extensive validation of the program. Such a validation study would typically be required in order to properly "debug" the program. It is hoped that future research support can be acquired that will allow this study to be continued. It is the authors' opinion that a continuation of this study would eventually encourage the use of the combination of time-lapse photography and computer simulation in actual practice.

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