# Micro-Simulation of Mine Haulage Systems

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## Abstract

*Truck shovel operations have a very significant contribution towards the productivity and overall cost of the mining operation. Macroscopic discrete event simulation models have been used so far in the industry and they prove to be a good tool to model this operation. But they miss one important aspect, i.e. the microscopic behavior of trucks while traveling. This paper concentrates on a model for capturing the real time behavior of trucks on the haul roads; taking into account the accelerations and decelerations of trucks based on gradient, turning angle, road conditions and platoon formations; which affects significantly the cycle times of the trucks. The objective of this research is: 1) to develop a model which demonstrates the microscopic behavior of a mining transport system and to draw out a comparison with the existing software and real life mining transportation data and; 2) extend this model to determine the optimal number of trucks (and shovels) in a given transportation system (considering the fact that increase in the number of trucks increases traffic delays on the common shared haul roads). A microscopic discrete event simulation model has been developed using the numerical equations of motion. The model has been verified against various desired characteristics of the transportation system incorporated into the model and also verified against Talpac software results.*

## 1. Introduction

Today's competitive market price and demand has made it imperative for the mining companies to focus on their productivity. Companies with poor productivity cannot stand the fierce competition of the market. Hence improvement in productivity has become a major concern of almost all the players in the mining sector.

One of the major contributing factors to the productivity is the transportation time. Reducing the truck cycle times have a considerable impact on meeting production targets. Therefore, enormous emphasis is given to minimizing the truck travel times by using dispatching systems, proper maintenance of haul roads etc. Several studies have been conducted so far for the fleet management problem in internal transportation systems. Most of these studies are macroscopic studies that focus on the total travel time of trucks and not on their microscopic behavior while travelling on the haul roads. Microscopic study has an advantage that it captures the platoon formation and traffic behavior on the haul roads which is one of the major causes of increased travel times. Other macroscopic studies do not account for the traffic behavior on the haul roads and so always under estimate the total travel time and in turn overestimate the production. Mixed fleet systems, where different trucks may have different velocity characteristics, have higher chances of platoon formation. Platoon formation will be mostly observed on the common shared haul roads which handle the flow from all the loading locations in the mine. Microscopic simulation in such cases would be much more appropriate and better compared to macroscopic simulations. A pictorial

Askari-Nasab, Hooman (2012), Mining Optimization Laboratory (MOL) – Report Four, © MOL, University of Alberta, Edmonton, Canada, Pages 340, ISBN: 978-1-55195-301-4, pp. 181-189.

difference between the two is illustrated in Fig. 1. It shows the position of two trucks, at time T=t and T=t+h, on a haul road for Macro as well as Micro-simulation.

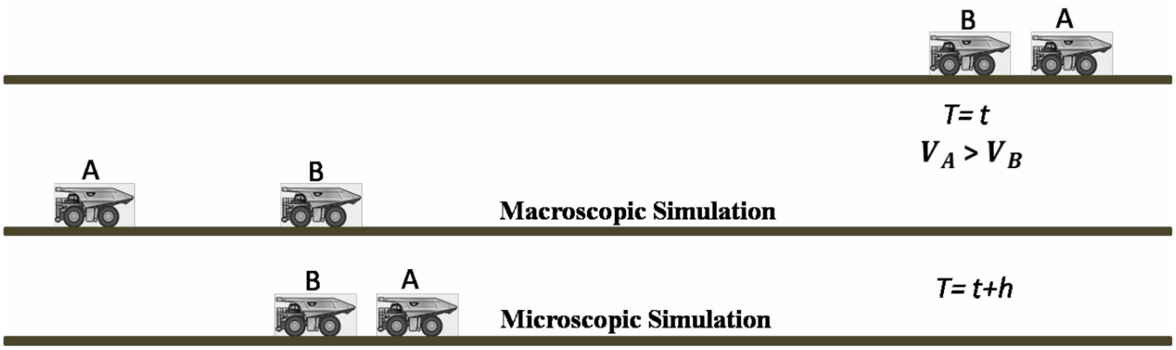

Fig. 1. Difference between the approaches of Macro and Micro Simulation

As we can see in Fig. 1, if no overtaking is allowed, truck A will have to slow down to the speed of truck B and follow it, and will be forced to have an increased travel time.

The objective of this paper is therefore to develop a micro-simulation model that could capture the traffic and platoon formations (as described in Fig. 1); and its impact on the travel time of trucks in any mine affecting the production output.

## 2. Literature review

When the research started in the field of truck movements and dispatching, initially algorithms were proposed to deal with fleet dispatching under deterministic conditions, i.e. constant travel time, no upset occurrence etc. It is more recently that special emphasis is made to find better dynamic solutions to real-time fleet dispatching as well as to fleet routing under non-stationary system state (Burt & Caccetta, 2007). Burt and Caccetta (2007) and many others pointed out the importance of tracking the inherent traffic behavior in the internal and congested haulage networks. They emphasized to incorporate the unpredictable and variable nature of various elements used in the analytical and simulation models which is induced by trucks bunched together in platoons and congestion in the shared closed networks.

Burt and Caccetta (2007) point out that the complex design and no flexibility of the haulage networks levy tight constraints on traffic in surface mining. In surface mining, a fleet of haul trucks travel between excavations and dumping stations, through common shared haul road segments. It is evident that mine productivity is very sensitive to truck dispatching decisions, which may minimize platoon formations and optimize the use of excavators. Several dispatching software have been proposed for this complex task, however Burt and Caccetta (2007) and Jaoua et al. (2012) describe them inefficient to account for the stochastic nature of the transportation system.

Jaoua et al. (2012) say that most of the dispatching algorithms are based on precompiled and deterministic truck cycle times and assume that for the next period trucks will spend on average the same time to accomplish the mission. However in reality of mining operation, the duration of truck travel is very sensitive to the real-time traffic state as well as the road condition.

Koppa et al. (2001) say that the vehicle movement in a traffic stream is loosely coupled with other vehicles via the driver’s processing of information and execution of control inputs. The driver perceives the speed or acceleration of other vehicles and executes the control which guides his movement. Considering the general case of multi-lane road, two situations appear relevant here which determines the movement of any vehicle 1) the vehicle ahead and 2) the vehicle alongside. In case of Mining Haul roads, having just one lane for one way traffic, only 1st situation comes into play.

In another study Rothery (2001) finds out that though it seems that the actions of any driver are continuous, there is some evidence that driver of any vehicle acts in a discontinuous way. There is a period of time during which the operator having made a decision to react is in an irreversible state and that the response must follow at an appropriate time, which later is consistent with the task. So, although the driver perceives the movement of other vehicles continuously, he/she processes it and then executes controls discontinuously. Hence a discrete event simulation, by modeling actions at discrete intervals of time can actually simulate the process. Another study by Kesting and Treiber (2008) suggests that drivers compensate for the human reaction time by anticipation. Hence a reaction time of zero seconds is considered in this paper.

Human visual perception to distinguish acceleration from constant velocity is very difficult unless the object is observed for a relatively long period of time (10 to 15 sec) (Boff & Lincoln, 1988). Mortimer (1988) estimates that a driver can detect a relative movement with respect to a leading vehicle when distance between them has varied by approximately 12 percent. Mortimer (1988) notes that the major factor for this perception is the change in visual angle.

The concept of car following model has been used in this paper to simulate the truck movements. According to Rothery (2001), car following model assumes that, in single lane traffic, there exists a correlation between two vehicles within a range of inter-vehicle spacing from zero to about 100 to 125 meters. This model assumes that each driver in a following vehicle is an active and predictable control element. It is this interaction that determines the acceleration or deceleration of the vehicle when two vehicles are interacting.

In normal case, when there is no interaction between vehicles, they try to move freely on their normal driving speed. According to Bonates (1996), maximum obtainable speed by any truck can be determined by the rimpull curves generally provided by the manufacturers. He describes the rimpull as the force exerted on ground by the drive wheels to get the truck in motion. This force is generated by the torque that the engine develops and it is a function of the gear ratios. Maximum achievable speed by truck on any haul road segment can be calculated by using the Eq. (1) given by Bonates (1996).

$$V_{\max} = \frac{366.97 \times Kw \times Efficiency}{TR \times W} \tag{1}$$

Where: $V_{\max}$ = Maximum obtainable velocity (Km/Hr)

$Kw$ = Vehicle engine power in Kw

$Efficiency$ = Motor efficiency (decimal)

$TR$ = Total resistance (decimal)

$W$ = Vehicle weight, in Kg

The maximum velocity calculated above is multiplied with a speed factor, as given in Table 1, to determine the average velocity of trucks along any haul road segment.

Table 1.Factors for converting maximum speed to average speed (Bishop, 1968)

| **Length of Haul Road Section (meter)** | **Factors for Converting Maximum Speed to Average Speed** | |
|---|---|---|
| | Unit Starting from Stop | Unit in Motion when Entering Road Section |
| 0-107 | 0.25-0.5 | 0.50-2.00 |
| 107-229 | 0.35-0.6 | 0.60-0.75 |
| 229-457 | 0.5-0.65 | 0.70-0.80 |
| 457-762 | 0.6-0.70 | 0.75-0.80 |
| 762-1067 | 0.65-0.75 | 0.80-0.85 |
| Over 1067 | 0.70-0.85 | 0.80-0.90 |

## 3. Proposed model

This paper proposes a Discrete Event Micro-Simulation model developed in Matlab to capture the traffic behavior of trucks on haul roads. Model evaluates the extra delays caused due to platoon formations on haul roads and uses it for cycle times and productivity calculations. Two types of interactions are possible on haul roads which result in platoon formations:

1. Interaction due to high relative velocity of trucks traveling between one loading and dumping location.
2. Interaction of trucks coming from different loading stations at intersections to follow a common shared path segment.

First type of interaction will be rare because of the time lag between the release of trucks due to the loading activity and small relative velocity (mixed fleet systems may have comparatively high relative velocity). Second type of interaction occurs more often. If the inflow rate of trucks on the shared path segment is very high (due to too many faces and small service times at shovels), it may even result in extra delay due to queue formation at the junctions.

The model uses Newton's equations of motion to determine the desired acceleration and deceleration to avoid any collision and maintain a safe distance while having any of the given interactions. Model uses Eq. (2) to Eq. (7) to determine the position and velocity of trucks at any time.

$$x_i\left(t+h\right)=x_i\left(t\right)+v_i\left(t\right)\times h+0.5\times a_i\left(t\right)\times h^2 \tag{2}$$

$$v_i\left(t+h\right)=v_i\left(t\right)+a_i\left(t\right)\times h \tag{3}$$

$$a_i\left(t\right)=K_i^1\times A_i\left(t\right)-K_i^2\times B_i\left(t\right)-K_i^3\times C_i\left(t\right) \tag{4}$$

$$A_i\left(t\right)=\min\left\{\left(v_i^{desired}-v_i\left(t\right)\right)/h,a_{\max}\right\} \tag{5}$$

$$B_i\left(t\right)=\frac{0.5\times v_i^2\left(t\right)}{x_i^{front}\left(t\right)-L_{truck}-SF-x_i\left(t\right)} \tag{6}$$

$$C_i\left(t\right)=v_i\left(t\right)/h \tag{7}$$

Where $i$ = truck index; $h$=discrete time increment; $x_i\left(t\right)$ = position of truck at time t; $v_i\left(t\right)$ =velocity of truck at time t; $a_i\left(t\right)$ = acceleration of truck at time t; $a_{\max}$ =maximum acceleration allowed; $v_i^{desired}$ = desired velocity of truck when not interacting with any other truck; $x_i^{front}\left(t\right)$ = position of truck in front of truck i; $L_{truck}$=length of truck; and $SF$ = minimum safety distance between the trucks when they stop. $K_i^1$, $K_i^2$ and $K_i^3$ are the binary constants which determine the needed acceleration depending on the extent of interaction between two trucks.

Here it should be noted that position of any truck is the position of the head of the truck. So the minimum safe distance for a following truck to avoid collision can be calculated using Eq. (8) (Rothery, 2001).

$$S=L_{truck}+\left(T_{reaction}\times v\right)+\left(0.5\times v^2/a_{\max}\right) \tag{8}$$

Considering the hypothesis of Kesting and Treiber (2008), this model assumes the reaction time to be zero; because the actions are based on the current state of the system, which is anticipated by the drivers in the past.

Un-signalized intersections are also modeled which work on the principle of first come first serve basis. So the truck from any path segment that has the minimum distance to intersection is allowed to pass through and the rest are decelerated to stop at a distance of SF until the intersection is free to serve others.

The model was verified against the desired characteristics. One of the important features the model is desired to have is to capture the interacting behavior of the trucks on the haul road. For this the model is run with a greater variability in the truck velocities to have clearly visible interactions. Given below is a position versus time plot for the trucks coming back to dump after loading. Fig. 2 clearly shows the deceleration of the trucks to follow the truck in front of it (as no overtaking is allowed).

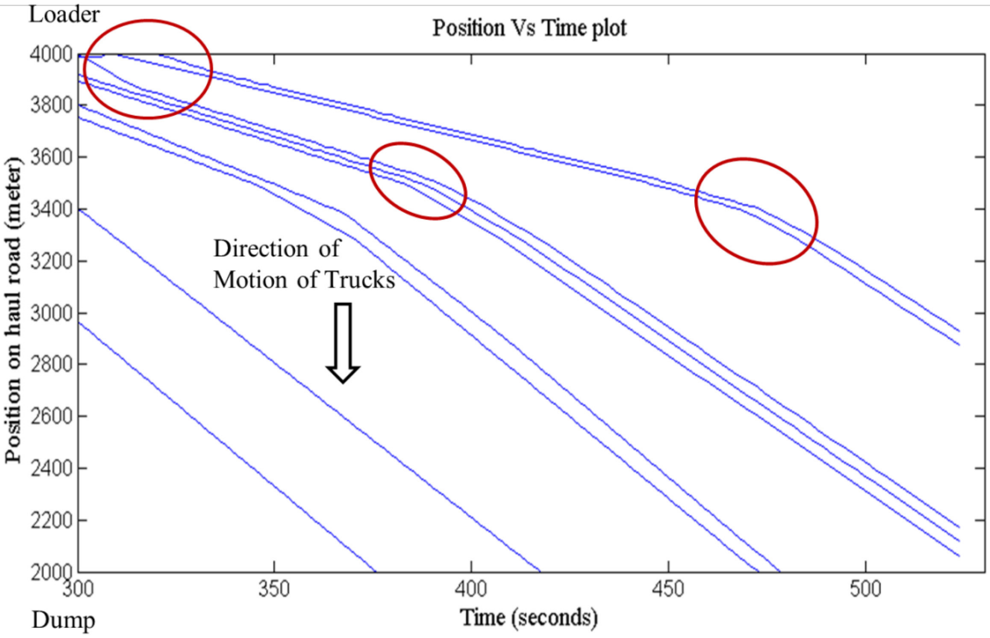

Fig. 2. Truck Positions (distance from dump) versus Time graph showing the interaction between trucks (no overtaking)

## 4. Case study

For the model verification a small hypothetical problem is considered which has only one shovel and one dump location. A straight (no turning angle and no gradient) haul road of length 2 Km is considered. Rolling resistance considered is 4%. Three different truck-shovel combinations are considered. Though the bucket capacity of shovels is different, cycle time for the shovels is kept the same in all the three cases. Bucket cycle time is considered to be normally distributed with mean bucket cycle time of 27 seconds and the standard deviation of 0.018. Fill factor of the bucket is considered to be 1.

### 4.1. Verification with theory

First verification study is done against the truck travel times calculated in excel based on the speed factors given by Bishop (1968). Based on lower and upper limit of speed factors, minimum and maximum travel times are calculated in excel and the results are compared with that obtained using 1 truck in the micro-simulation model, which is given in Table 2. The micro-simulation output is found to be well within the range of theoretical output. The model therefore conforms to the theoretical results.

Table 2.Theoretical range of travel times and that obtained by Micro-Simulation Model

| Truck | Length of Haul Segment (m) | Theoretical Travel Time | | Micro-Simulation Travel Time (Minutes) |
|---|---|---|---|---|
| | | Lower Limit (Minutes) | Upper Limit (Minutes) | |
| Caterpillar 770 (36 Tonne) | 2000 | 5.99 | 7.27 | 6.77 |
| Terex Lectra Haul MT-3300 (136 tonne) | 2000 | 6.88 | 8.46 | 7.76 |
| Caterpillar 793F (225 tonne) | 2000 | 6.31 | 7.63 | 7.08 |

Using the deterministic travel times calculated above, number of trucks for maximum output (no queuing) is also calculated theoretically, which can be obtained using the Eq. (9) given by Gransberg (1996).

$$\left(n-1\right)\times LoadingTime = CycleTime \tag{9}$$

The formulae equate the total time taken by the loader to load (n-1) trucks by the time first truck returns back to it to get loaded. It assumes that for optimal productivity there should be no waiting time for any truck; and loader should never be idle. Cycle time in this formula includes hauling, spotting at dump, dumping and returning. Considering multiple dumping sites, no queuing at dump is considered. Model also consider no spotting time at dump and mean dumping time of 30 seconds. For theoretical calculations only mean values are used.

Table 3.Theoretical optimal number of trucks

| Truck | Loading Time (Minutes) | Theoretical Travel Time | | Optimal Fleet Size | |
|---|---|---|---|---|---|
| | | Lower Limit (Minutes) | Upper Limit (Minutes) | Lower Limit (n) | Upper Limit (n) |
| Caterpillar 770 (36 tonne) | 1.35 | 5.99 | 7.27 | 5.81 | 6.76 |
| Terex Lectra Haul MT-3300 (136 tonne) | 1.8 | 6.88 | 8.46 | 5.09 | 5.98 |
| Caterpillar 793F (225 tonne) | 1.35 | 6.31 | 7.63 | 6.04 | 7.02 |

The fractional value of fleet size indicates that there will be no queuing at the floor value and queuing will start taking place at its ceiling value. The values obtained here are compared with that obtained with the Microscopic model presented here (see the hourly production graphs in Fig. 3, Fig. 4 & Fig. 5) and found to be conforming. We can see almost a constant slope of hourly production plot with fleet size up to the maximum number of trucks, where queuing start taking place and the rate of increase in production suddenly decreases and then becomes zero. So, the model is theoretically valid.

### 4.2. Verification with Talpac results

A haulage system similar to that considered in Micro-Simulation model is created in Talpac with Terex (136 tonne) trucks and 32.4 tonne bucket capacity loader. No spotting time is considered in Micro-simulation model and therefore double side loading is selected in Talpac. All distributions are matched in both the models. Hourly production output is then calculated and plotted against the production output of Micro-simulation model. A plot of the output is given in Fig. 3.

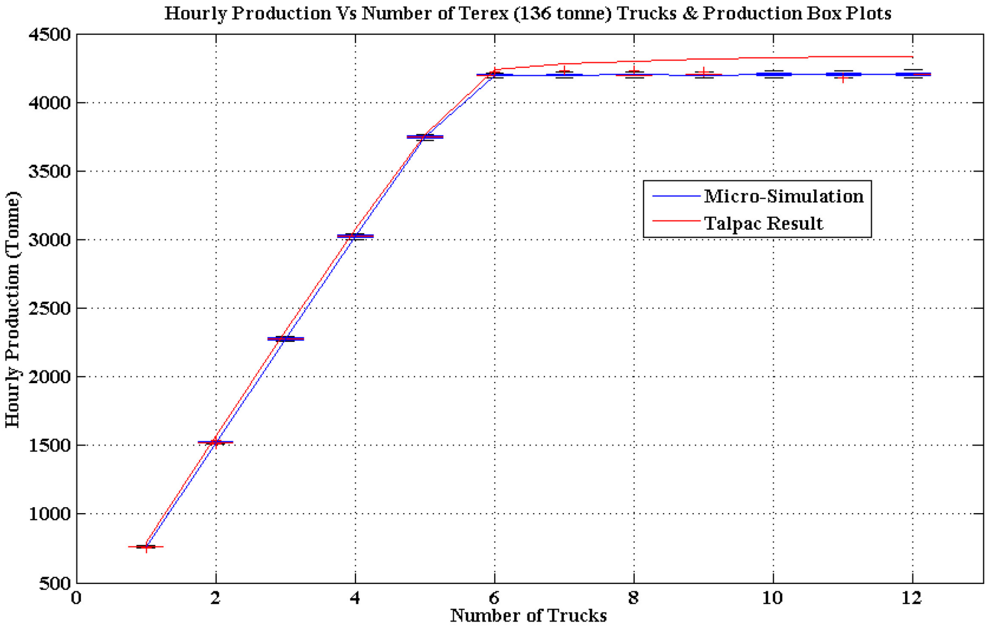

Fig. 3. Hourly Production obtained and Box Plots for number of Terex (136 Tonne) Trucks from Talpac and Micro-Simulation Model

Second comparison was made using a very low capacity Caterpillar (36 Tonne) truck and 10.78 Tonne bucket capacity shovel. Keeping other parameters the same, as before, hourly production is obtained from Talpac and Micro-Simulation Model. A graph obtained is given in Fig. 4.

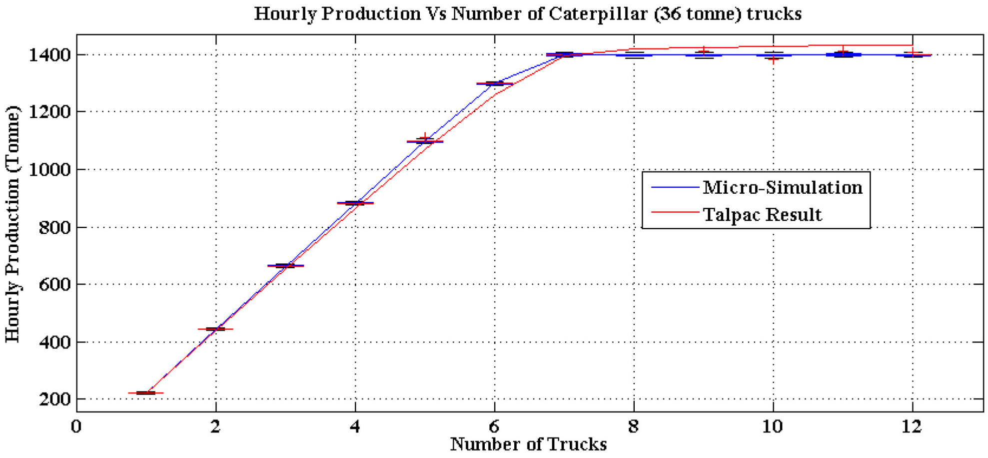

Fig. 4. Hourly Production versus number of Caterpillar (36 Tonne) trucks and Production Box Plots for the results obtained using Talpac and Micro-Simulation model

Another comparison is done considering a high capacity Caterpillar (225 Tonne) truck and 73.06 tonne bucket capacity shovel. Keeping all other parameters the same, output of Talpac and Micro-Simulation model was generated, which is given in Fig. 5.

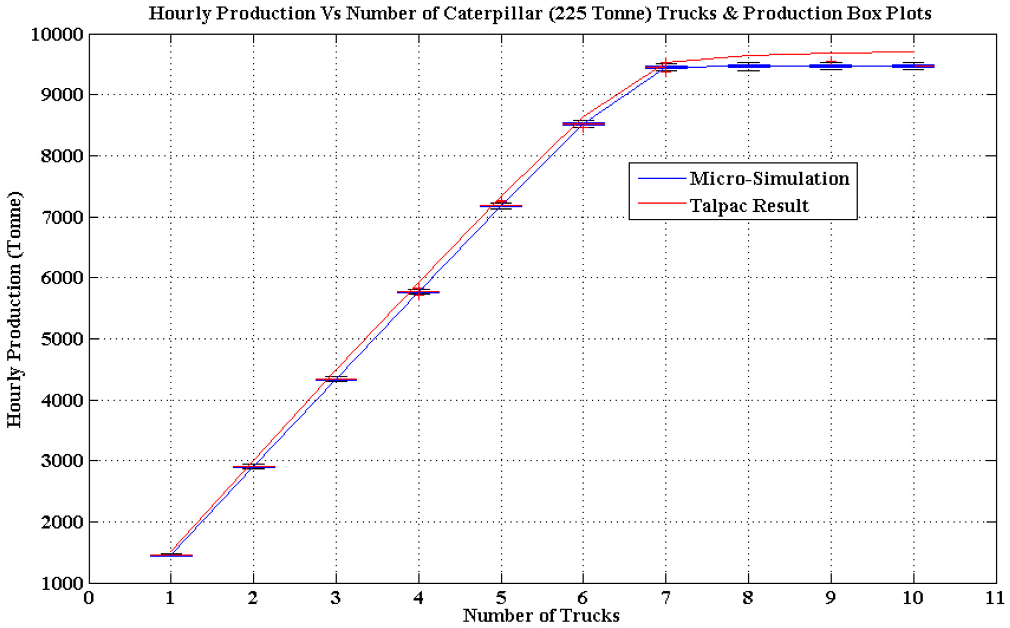

Fig. 5. Hourly Production obtained and Production Box Plots for number of Caterpillar (225 tonne) trucks using Talpac and Micro-Simulation Model

We can see that the developed model conform to the Talpac results, in respect of the variability in production with the fleet size. The small difference observed in production is because of a relatively greater cycle time in micro-simulation.

## 5. Conclusions

The cases discussed here show that the rate of increase in production per unit truck in the fleet size is same in Talpac as that obtained by the model discussed in this paper. The relatively greater value of travel time observed in this model is because of accelerations and decelerations considered and also any interactions that occur between trucks.

The sealing value of production is less in case of the model discussed here. It is probably because of having a relatively greater travel time, Micro-Simulation observes 100% shovel utilization later, at a higher fleet size (fractional value) compared to Talpac (see Eq. (9)), but at the same time because of having a smaller travel time, Talpac finds surplus time to do more cycles and have higher production. The second reason is playing a dominating role over here, because the hourly production is calculated by averaging the total shift production which buys surplus time to Talpac (lower travel time) to have more number of cycles and have a greater production.

Verification study of the model discussed in this paper proves that the model is capable of simulating the transportation system of mines. Although no significant difference can be observed at this stage in the travel time behavior of trucks presented here compared to that of Talpac, it is expected that with increase in loading locations the number of trucks entering the common shared path will increase and the trucks in that case will have greater variability in their speed. In such a condition there will be greater interaction between the trucks that will affect the individuals travel time.

## 6. References

[1] Bishop, T.S. (1968). Trucks. In E.P. Pfleider (Ed.), *Surface Mining*. New York: The American Institute of Mining, Metallurgical and Petroleum Engineers.

[2] Boff, K. R. , & Lincoln, J. E. . (1988). Engineering Data Compendium. Ohio: USAF, H. G. Armstrong Medical Research Laboratory, Wright-Patterson AFB.

[3] Bonates, E. (1996). Interactive truck haulage simulation program. *Mine Planning and Equipment Selection*, 51-57.

[4] Burt, C., & Caccetta, L. (2007). Match factor for heterogeneous truck and loader fleets. *International Journal of Mining, Reclamation and Environment 21*, 262-270.

[5] Gransberg, Douglas D. (1996). Optimizing Haul Unit Size and Number Based on Loading Facility Characteristics. *Journal of Construction Engineering and Management, 122*, 248-253.

[6] Jaoua, A., Riopel, D., & Gamache, M. (2012). A simulational framework for real-time fleet management in internal transport systems. *Simulational Modeling Practices and Theory 21*, 78-90.

[7] Kesting, A., & Treiber, M. (2008). Calibrating Car-Following Models by Using Trajectory Data. *Transportation Research Record: Journal of the Transportation Research Board, No. 2088*, 148-156.

[8] Koppa, Rodger J. (2001). Human Factors. In Nathan H. Gartner, Carroll Messer & Ajay K. Rathi (Eds.), *Traffic Flow Theory: A State-of-the-Art Report* (pp. 68-101): Committee on Traffic Flow Theory and Characteristics.

[9] Mortimer, R. G. (1988). Rear End Crashes. In G. A. Peters & B. J. Peters (Eds.), *Automotive Engineering and Litigation* (Vol. 2). New York: Garland Law Publishing Co.

[10] Rothery, Richard W. (2001). Car Following Models. In Nathan Gartner, Carroll J. Messer & Ajay K. Rathi (Eds.), *Traffic Flow Theory: A State-of-the-Art Report* (pp. 102-145): Committee on Traffic Flow Theory and Characteristics.