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INTEGRATION OF CONSTRUCTION AND TRAFFIC ENGINEERING IN SIMULATING PIPE-JACKING OPERATIONS IN URBAN AREAS

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ABSTRACT

Construction simulation and traffic simulation are complementary to successful planning of microtunneling and pipe-jacking operations in urban areas. With increasing concerns on sustainable development, it is imperative to integrate construction engineering and traffic engineering in simulation modeling in order to plan for efficient site operations while reducing the impact of construction upon traffic. In this research, we demonstrate a "larger system simulation" approach to effectively plan pipe-jacking operations in urban areas in considerations of (1) truck delivery routes and timing; (2) sizing and location of temporary laydown area on site; (3) traffic lane closure distance; and (4) working hours scheduling, aimed at minimizing the negative impact of construction on traffic. Our research goal is to deliver a temporary traffic arrangement plan along with an efficient site operations plan, thus keeping a balance between construction productivity and traffic mobility. A case study is given based on a pipe-jacking site in the urban area of Hong Kong.

1 INTRODUCTION

Construction simulation and traffic simulation are complementary to successful planning of microtunneling and pipe-jacking operations in urban areas. With increasing concerns on sustainable development, it is imperative to integrate construction engineering and traffic engineering in simulation modeling in order to plan for efficient site operations while causing minimal traffic impact. Microtunneling and pipe-jacking operations are commonly classified as trenchless technologies which minimize the open cut area, but lane closure is still required around the jacking and receiving shafts. Extended duration for lane closure leads to traffic queuing, more user delay cost and social cost. Reduced traffic mobility also increases material handling cycle time in construction, holding up ring pipe deliveries. As only limited buffer storage is available onsite, the traffic delay potentially idle the crew and the TBM, lowering productivity while increasing the direct cost and project duration. Planning the temporary traffic arrangement (TTA) involves communication and consultation with relevant authorities (including the traffic department and the police department), and consideration of traffic safety and possible complaints from road users and local businesses.

In this research, we demonstrate a "larger system simulation" approach to effectively plan pipe-jacking operations in urban areas in considerations of: (1) truck delivery routes and timing; (2) the sizing and location of temporary laydown area on site ; (3) the traffic lane closure distance; and (4) working hours scheduling, aimed at minimizing the negative impact of construction on traffic especially during the peak hours. Our research goal is to deliver a temporary traffic arrangement (TTA) plan along with a site operations plan, thus reaching a balance between construction productivity and traffic mobility. A case study is given based on a pipe-jacking site in the urban area of Hong Kong. The construction simulation platform of SDESA (simplified discrete event simulation approach) is utilized to simulate the larger pipe-jacking system integrating construction engineering and traffic engineering.

2 RESEARCH NEEDS FOR INTEGRATION OF CONSTRUCTION AND TRAFFIC ENGINEERING

TTA planning involves work zone establishment, lane closure design, and traffic throughput reduction analysis, which plays a pivotal part in achieving smooth and successful operations at microtunneling sites. Owing to the limited road width in the urban area, the traffic impact induces prolonged queuing to road users, potentially leading to public complaints and substantial social cost. The TTA plans are usually prepared by traffic consultants based on available traffic flow information and previous TTA plans in the vicinity. In order to verify the effect of the TTA plans at critical locations, trial runs in the first one or two days before the actual project commencement would be requested by relevant traffic authorities. However, this practice entails experimentation of the TTA in the real world, possibly causing major traffic disruptions and incurring exorbitant social cost. In view of the public interest, modeling the traffic-construction interaction on pipe-jacking sites situated in dense urban areas is well warranted, as echoed at the 'Research Needs for New Construction using Trenchless Technologies' conference held on 17th June 2003 at the University of Birmingham UK (Chapman et al. 2007). On the conference, the whole life costing of trenching and trenchless technology including social cost ranked the highest during the voting on generic issues of planning, design and monitoring. The present research applies discrete simulation modeling to automate the lane closure layout design and investigate the impact of construction upon the traffic.

3 PREVIOUS RELATED RESEARCH

Lau et al. (2009) established a framework for developing intelligent decision support tools in order to facilitate effective microtunneling construction planning with a focus on general site operations planning. Lau et al. (2010A) implemented a simulation model for a microtunneling site and demonstrated the application values of the simulation model for construction planning. To assess the traffic impact imposed to road users and formulate material delivery schedules after the implementation of TTA plans on the microtunneling site, Lau et al. (2010B) proposed an simulation model for lane closure planning in congested urban areas.

4 CONSTRUCTION SIMULATION APPLICATION

A simulation model of typical microtunneling operations was set up using simplified discrete event simulation approach (SDESA), which is an activity-based simulation modeling platform developed from in-house research for both detailed construction operations simulation and critical path method (CPM) based scheduling simulation. Interested readers may refer to Lu (2003) and Lu et al (2007) for details on simulation algorithms and generic process mapping. The site operations model portrays logical sequences, resources, technical constraints, and common activities on microtunneling sites. Further site-specific constraints can be added to individual simulation cases.

At the planning stage, the simulation tool is used to investigate the effects of various combinations of resource allocations, pipe section delivery cycle times and site layout designs. The statistical distributions of the pipe-section installation cycle time provide input models for detailed jobsite planning. Before the project commences, the project planner could take a typical microtunneling model template for a quick launch of simulation modeling. The simulation model is fine-tuned based on the actual site layout plan and estimated activity durations. Further site constraints such as the installation of spacers due to shaft size limitation or the number of intermediate jacking stations are defined in the model. Spatial constraints can be introduced according to the maximum quantities of pipe sections to be stored on site. This would further pose a logistical constraint to the project planner who aims to achieve just-in-time deliveries.

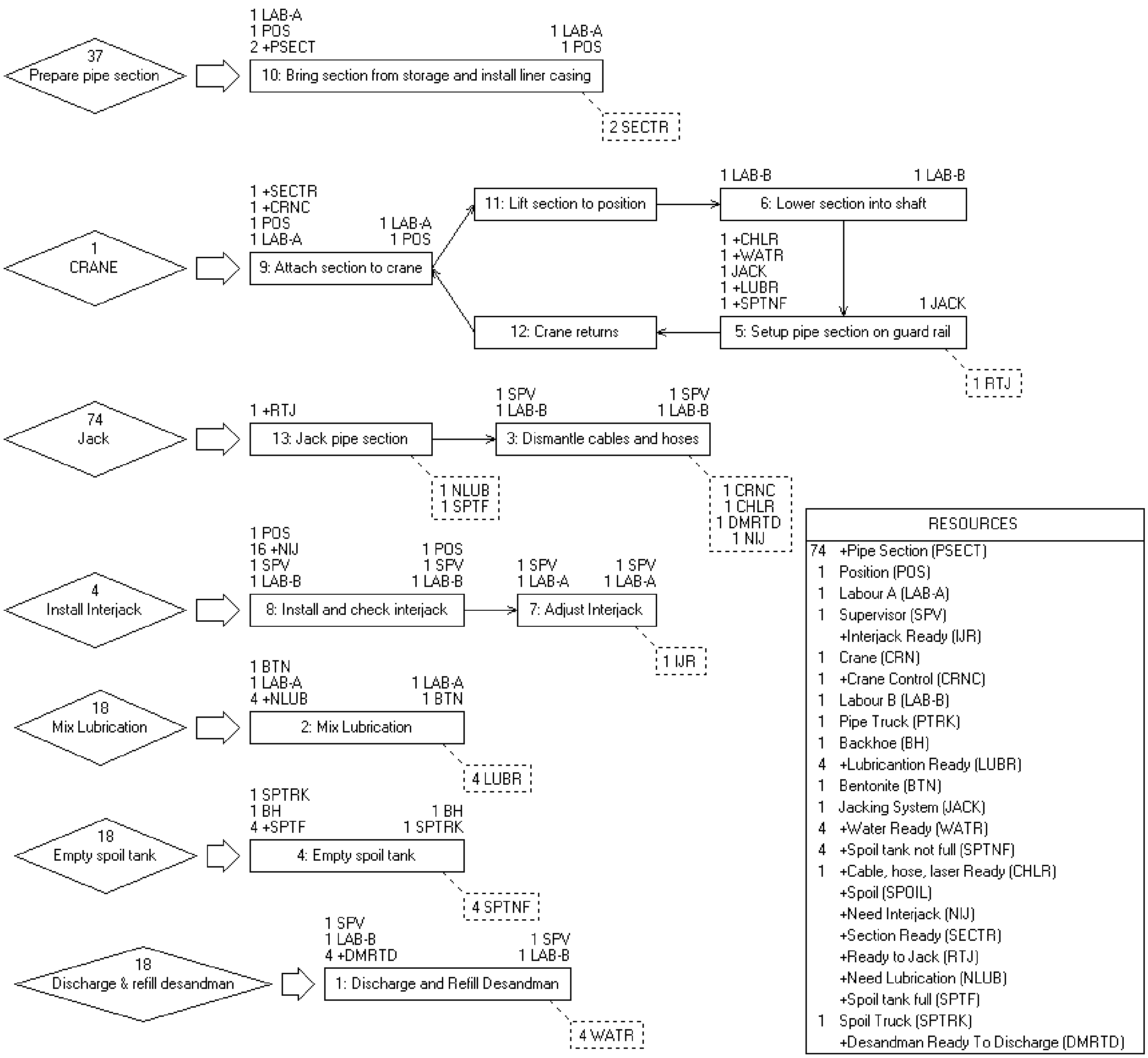

Figure 1: Simulation Model for microtunneling construction

The site operations model was defined during the site planning stage, consisting of logical sequences, activity durations and resource allocation. The "Jack" workflow was the major workflow in the model and facilitated by other supporting work flows such as "Mix Lubrication" and "Empty Spoil Tank", and "Pipe delivery" and "Crane (lifting)". The stochastic activity durations for site operations were entered into the model for statistical analysis of overall system performances.

The daily site working cycle is defined as follows: 1) Preparation time (Warm-up period): 0800-0830; 2) Working time 1: 0830-1230 (240 minutes); 3) Lunch hour: 1230-1330; 4) Working time 2: 1330-1730; 5) Cool-down time: 1730-1800. The statistical distribution of working time is shown in Figure 5.

5 WORK ZONE TRAFFIC THROUGHPUT SIMULATION

At the site planning stage, the Temporary Traffic Arrangement (TTA) is planned based on 1) the required location and size of the jacking pit; 2) site access, including point of ingress and egress, any time restrictions; 3) the temporary storage or lay down areas near the jacking pit.

The road between “Entry” and “25m away from exit” as shown in Figure 4 is divided into 25 metre long sections, from Chainage 0 to Chainage 225. The location set is defined in the model as shown in Figure 2. All sections consist of two lanes in the baseline case, while one lane will be closed for the section between “Approaching Taper” & “End Taper” (i.e. L1, L2 and L3) when implementing the TTA plan in the work zone.

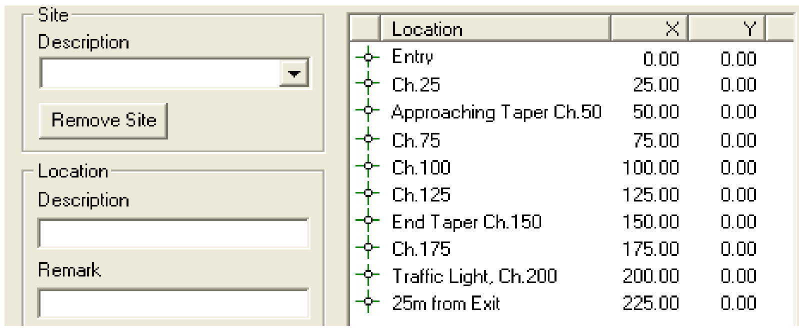

Figure 2: Location Set for TTA plan of Microtunneling Site

Table 1 summarizes the traffic flow details for various TTA sections, providing simulation input models. L_i is the length of a particular lane section is defined as 25 metres along the road; L_v is the length of a standard vehicle + gap between vehicles and is specified as 12.5m. Therefore, the traffic carrying capacity for a particular road section can be determined (Q_i) = L_i/L_v * number of lanes (1 or 2 for lanes within and outside the work zone).

Table 1: Simulation Model Input for Traffic Flow Details at the Concerned TTA Section.

Chainage	Length (m)	Speed (km/h)	Number of cars per lane	No. of lane	Total Number of cars
50m from Entry to Approaching Taper					
Ch.0-25	25	24-30	2	2	4
Ch.25-50	25	24-30	2	2	4
Approaching Taper to End Taper					
Ch.50-75	25	24-30	2	2 (1 with TTA)	4 (2 with TTA)
Ch.75-100	25	24-30	2	2 (1 with TTA)	4 (2 with TTA)
Ch.100-125	25	24-30	2	2 (1 with TTA)	4 (2 with TTA)
Ch.125-150	25	24-30	2	2 (1 with TTA)	4 (2 with TTA)
End Taper to Traffic Light					
Ch.150-175	25	24-30	2	2	4
Ch.175-200	25	24-30	2	2	4
Traffic Light to Exit					
Ch.200-225	25	24-30	-	2	-

Limited vehicle positions are defined to model the queues in traffic flows. Note that only when the previous position is cleared the current position would be released. Thus, the logical connection between consecutive road sections is that an empty spot in the next road section triggers the move-in of one vehicle from the previous road section, which releases the spot in the previous road section.

The incoming traffic flow data for the simulation model in the morning (0600-1200) is summarized in Table 2. The peak hours (0800-1000) and non-peak hours (0600-0800 and 1000-1200) are defined by uniform distributions of inter-arrival time being [1,2] min and [2,4] min respectively. The traffic flows are equivalent to 1200 and 2400 vehicles per hour (two lanes) accordingly.

Table 2: Simulation Model Input of Incoming Traffic Flow.

Simulation Time	**Peak hour/ Non-peak hour**	**Inter-arrival Time (s)**	**Average Inter-arrival Time (s)**	**Vehicle/hour**
0600-0800	Non-peak	UNIF[2,4]	3	1200
0800-1000	Peak	UNIF[1,2]	1.5	2400
1000-1200	Non-peak	UNIF[2,4]	3	1200

For the outgoing traffic flow, the vehicles pass through the work front and stop at a traffic light with the following details: the traffic light cycle time is 60 seconds; the green light phase (Tg) is 18 seconds; and the red light phase (Tr) is 42 seconds. Qg is the quantity of vehicles that can exit during the time period of Tg, which estimated to be 38 on average.

The traffic simulation model is established using SDESA (Lu 2003; Lu et al. 2007) as shown in Figure 3. The flow entity diamonds leading a series of activity blocks denote the number of vehicles (vehicle arrival in different timeslots) or the quantity of traffic signals (e.g. the quantity of green light cycles for each hour) to pass through the system. The activity blocks represent activities that consume time and resources in processing a flow entity. Reusable resources (the number of traffic lanes along the chainage, the space blocks available for vehicle occupancy in the lanes) are defined in the resource pool to model traffic spatial constraints. The top left corner of activity blocks shows the resources required to execute an activity. Disposable resources are differentiated from reusable resources by its temporary nature in form of intermediate products or information units generated by an activity (e.g. "car at different chainages, CAR_0" at the right bottom of an activity "Vehicle arrival") and requested by another (as shown in the top left corner of the activity block "(Vehicle Travel) From Ch.0 to Ch.25" and prefixed with "+").

An activity would commence as soon as all the logical criteria (resources, signals) specified on an activity block are satisfied. Upon the completion of an activity, the reusable resources (the available space blocks in lanes in this traffic model) would be released and disposable resources generated at the top and bottom right corner of activity blocks, respectively (those disposable resources are usually signals to link up different flow entities according to the logical sequences, for example, a vehicle travels across a section and then enters into the next section).

The top three flow entities initiate vehicles entering the system during the timeslots 0600-0800, 0800-1000 and 1000-1200 respectively with the pre-defined vehicle inter-arrival time distributions based on the peak-hour and non-peak-hour traffic statistics. Note one car at Chainage 0 (CAR_0) is generated at the right bottom corner of three activities "Vehicle arrival at 0600-0800", "Vehicle arrival at 0800-1000" and "Vehicle arrival at 1000-1200".

The subsequent flow entity "Vehicle Approaching" can then be activated once the signal is passed to the activity "(Vehicle Travel) From Ch.0 to Ch.25" which commences when the all resources required are ready including an empty lane "1 LANE 0" and one Car at Chainage 0 "+1 CAR_0". The completed activity would further trigger its subsequent activity "(Vehicle Travel) From Ch.25 to Ch.50".

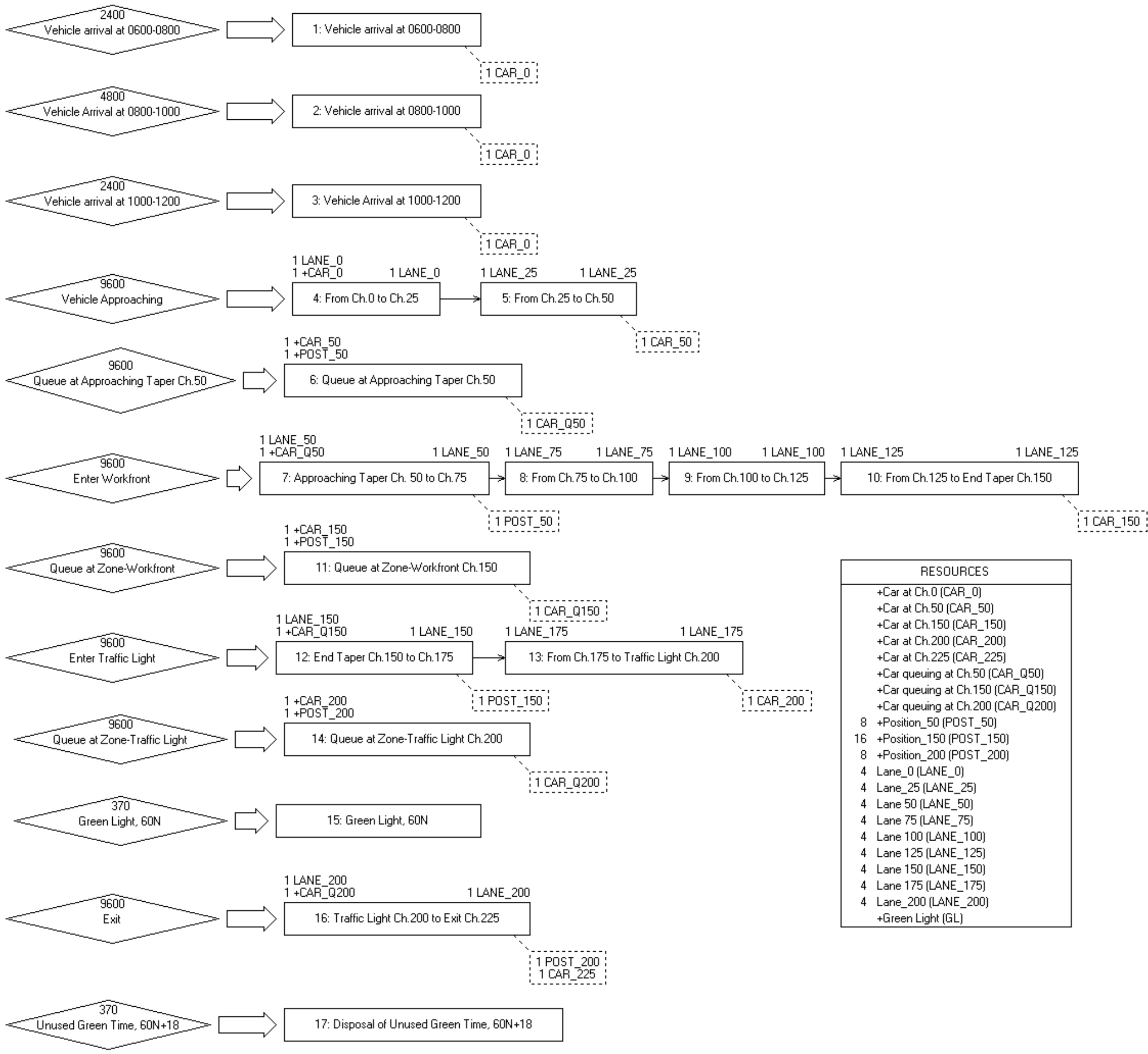

Figure 3: Traffic Model Using SDESA for TTA of Microtunneling Site

It is noteworthy that a "Start-Finish" relationship is defined in the model for the queuing activity. Unlike typical construction processes where the activities are usually linked up by Finish-Start relationship (e.g. form working, concreting and removal of formwork), traffic modeling is on the opposite. The queue builds up from the front while the vehicles approaching behind wait until the vehicles in front are cleared. As shown in Figure 3, a position at Ch. 50 "+ 1 POST_50" is generated upon the completion of "Activity 7: Approaching Taper Ch. 50 to Ch.75". The signal would in turn initiates "Activity 6: Queue at Approaching Taper" since the space in front is ready for a car to move in.

The initial traffic model is defined as a two-lane carriageway as a baseline for traffic impact assessment. The traffic flow information including incoming, passing and outgoing flows is given in the tables above. The model is then modified according to the TTA plan, for which one of the two lanes is closed during the course of construction. The traffic statistics of the system before and after TTA implementation can be compared during the peak and non-peak hours. The traffic impact measures including the queue length and the "Added System Residence Time of Each Car" can be obtained from simulation outputs.

Based on simulation results, the site planning engineer can revise the site configuration, adjust the time for TTA implementation (e.g. 24/7 or 1000-1600 at working day) and schedule loading / unloading of equipment and material deliveries (e.g. only during non-peak hours). The expected queuing time can be also used as a reference for planning the construction delivery cycles. For example, given expected delay of [20, 30] minutes during the peak-hours resulting from simulation, the site engineer can consider non-peak hour deliveries so as to avoid the delay or arrange for material deliveries only to other sites with less traffic congestion in peak hours.

For a multiple-lane carriageway as shown in Figure 4, the planner can make use of the simulation tool for simulating the closure of two of three lanes during the off-peak hours for loading/ unloading of jacking equipment at a congested site in which there is not enough space for the accommodation of a large crane within the site.

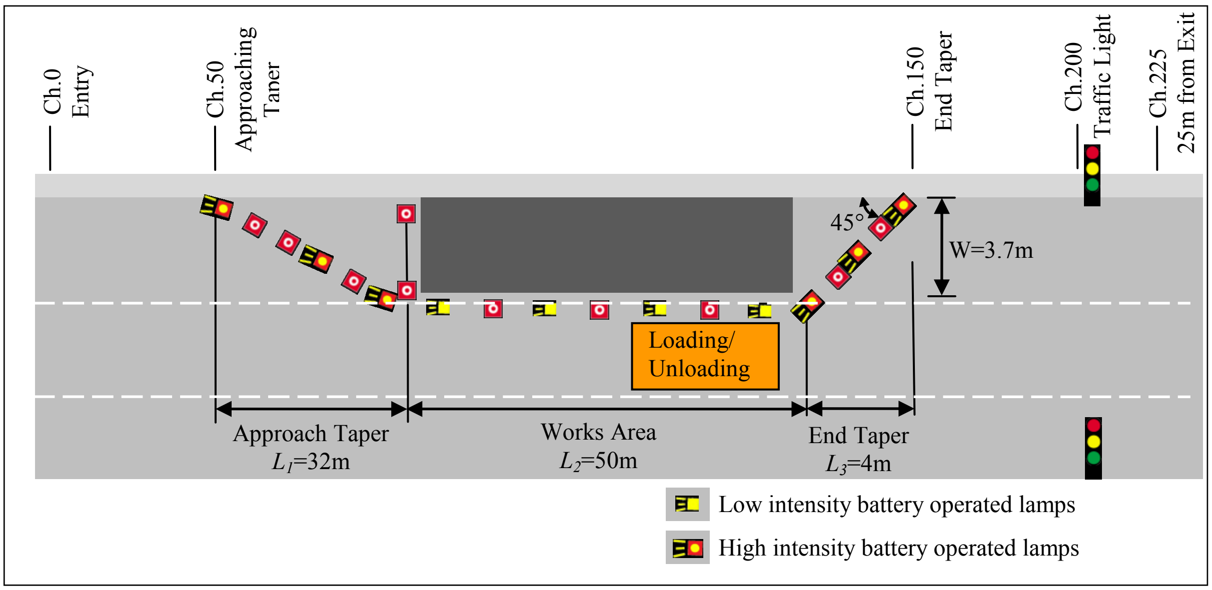

Figure 4: TTA plan of Temporary Loading / Unloading Beside a Microtunneling Site

6 INTERGRATION OF CONSTRUCTION SIMULATION AND TRAFFIC SIMULATION

The construction simulation is then integrated with the traffic simulation through linking the pipe delivery trucks into the traffic model. Different delivery patterns, including all-day delivery and non-peak hour delivery only, are tested in the integrated model. Such integration produces a prediction of pipe delivery delay for construction management and a prediction of traffic delay for traffic management. The integrated model facilitates arriving at a win-win solution in regard to construction productivity and traffic mobility.

7 RESULTS AND DISCUSSION

The behavior of logistic cycle times and resource utilization rates in different simulation scenarios would vary considerably. The simulation model can be used as a platform for productivity analysis based on different jacking cycle times (or advance rates for the tunnel boring machine). Further decisions can be made based on the utilization rate of resources resulting from the simulation model as shown in Figure 6. For example, when long cycle time is foreseen, the manager may consider revising the material delivery schedule while reallocating any under-utilized resources on site in order to increase cost efficiency. In this sense, the simulation models can render competent decision support to project planners in optimizing microtunneling production parameters.

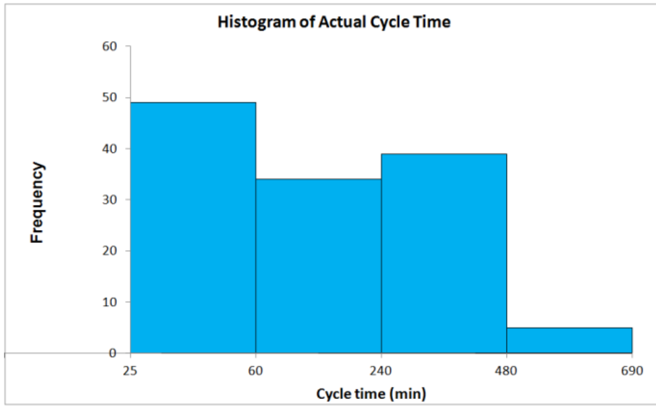

Figure 5: Histogram of actual cycle time at So Kwun Wat microtunneling site

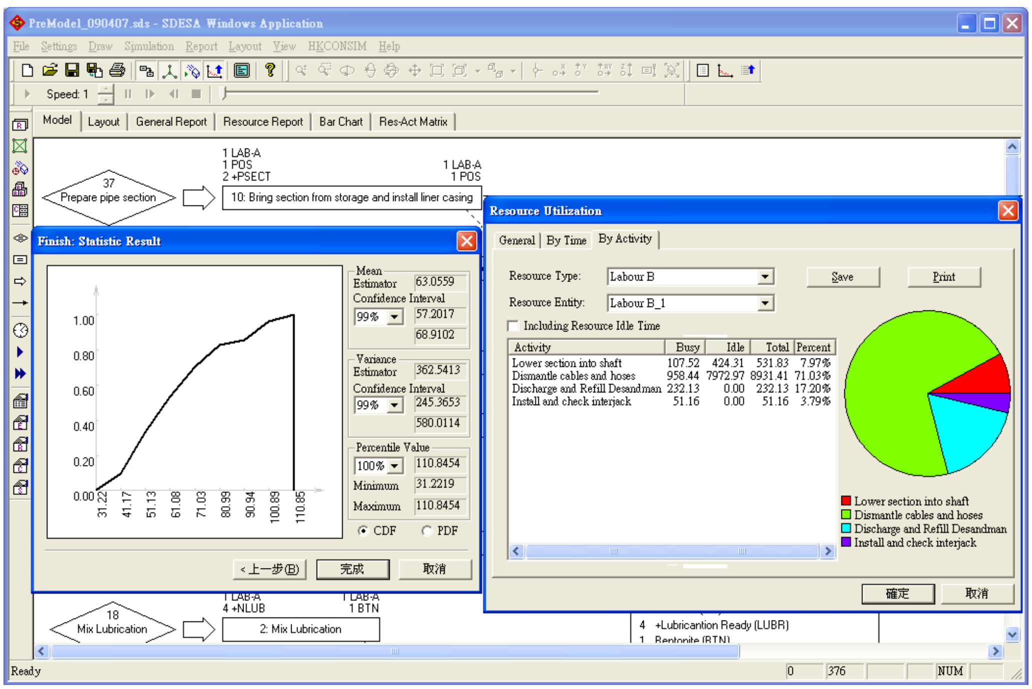

Figure 6: Screenshot of SDESA model outputs on activity duration and resource utilization statistics

From the simulation results, the baseline case was found to carry the smooth traffic, as indicated by a maximum queuing length of 5 vehicles throughout the whole construction period. On the other hand, the traffic queuing was observed with the implementation of TTA plan as shown in Figure 7, the queue length builds up starting from 08:00 with the introduction of the peak hour traffic flow and reaches a maximum quantity of 255 vehicles per lane at 10:00. The digestion of the whole queue length requires further 30 minutes after the incoming traffic flow changes from peak-hour rate to non-peak hour rate. The effect of construction on traffic can also be indicated by the "Added System Residence Time of Each Car" statistics, which measures the additional time for the road user to spend in passing through the system. In this case, the average "Added System Residence Time of Each Car" is 189 seconds and the standard deviation is 231 seconds. With the assistance of the simulation tool, the construction planner can review the possibility of extending Tg for increasing the Qg (which is equivalent to distributing the queue length between the two directions of traffic flows by adjusting traffic light cycle times at the intersection.) The

"Added System Residence Time of Each Car" would be used as an effective indicator for resource planning and logistics planning on site. For example, given the pipe sections would be delivered to site in the morning, the planner should assign the delivery the day before in order to avoid the peak hours during which the queuing time would significantly increase. He or she may re-schedule the material delivery plan for different concurring construction sites so as to prevent prolonged idling time of critical construction equipment resources, such as TBM, site crews, and trucks.

Another potential application on the simulation results is to forecast the expected driving delay to the road users based on the queue length and the Added System Residence Time of Each Car. For example, threshold values can be defined as: the "Amber" driving delay signal for expected queue length longer than 100 vehicles; the "Red" driving delay signal for expected queue length longer than 200 vehicles; and the "Black" driving delay signal for expected queue length longer than 300 vehicles. The expected driving delay can be updated on the Google Map such that the road users can decide whether to use the route passing through the TTA plan or choosing alternative driving routes.

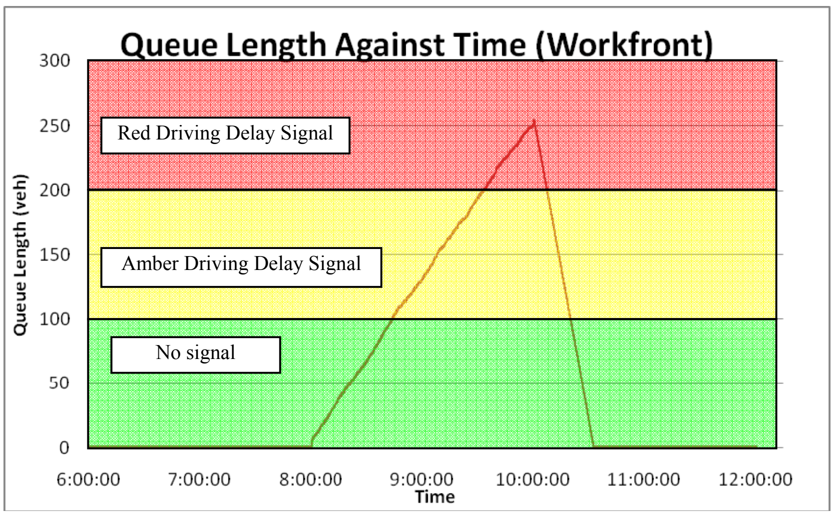

Figure 7: Queue length against time with TTA plan

8 CONCLUSION

Construction simulation and traffic simulation are complementary in successful planning of microtunneling and pipe-jacking operations in urban areas. With increasing concerns on sustainable development, it is imperative to integrate construction engineering and traffic engineering in simulation modeling in order to plan for efficient site production while causing minimal traffic impact. Planning the temporary traffic arrangement (lane closure) involves communication and consultation with relevant authorities (including the traffic department and the police department), and consideration of traffic safety and possible complaints from road users and local businesses.

In this research, we have demonstrated a "larger system simulation" approach to effectively plan pipe-jacking operations in urban areas factoring in: (1) truck delivery routes and timing; (2) temporary laydown area on site in terms of sizing and location; (3) traffic lane closure distance; and (4) working hours scheduling, all aimed at minimizing the negative impact of construction on traffic especially during the peak hours. Our research goal is to deliver a temporary traffic arrangement plan along with a site operations plan, thus keeping a balance between construction efficiency and traffic mobility. A case study is given based on a pipe-jacking site in the urban area of Hong Kong. The construction simulation platform of SDESA (simplified discrete event simulation approach) was utilized to simulate the larger pipe-jacking system integrating construction simulation and traffic simulation.

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