Developing a Traffic Closure Integrated Linear Schedule for Highway Rehabilitation Projects

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Abstract: In recent years, the state departments of transportation have implemented a number of highway rehabilitation projects across the country. These projects differ fundamentally from new highway projects in that they require an uninterrupted flow of traffic throughout both the duration and geometric length of the project. Synchronization of traffic closure with the construction activities is crucial in such projects to avoid the traffic conflicts and prevent idle time for equipment and labor. Although most highway rehabilitation projects involve predominantly linear activities, the techniques of linear scheduling are not readily applicable to highway rehabilitation projects due to the conflict between the workzone and traffic flow. This paper documents the development of a traffic closure integrated linear schedule (TCILS) that addresses both traffic closure and work progress issues. The TCILS generates a single schedule for both the construction activities and the associated traffic closures. Visual and graphical features are also applied in the system, which makes it particularly applicable for highway rehabilitation projects. An actual concrete pavement rehabilitation project using the TCILS is presented as a sample of application. The findings from the sample project, although they are limited, show that the TCILS can be applied to an actual project. With recommended future development, the system is believed to be beneficial for both construction practitioners and academics.

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Introduction

The success of any construction project is largely dependent on the selection of the planning, scheduling, and controlling system adopted for the project. Many different kinds of scheduling tools are available, which vary depending on how activities are represented and analyzed, and the logical relationships between activities. For complex and fragmented construction projects such as commercial buildings, bridges, and refineries, network-based scheduling tools such as the critical path method (CPM) and the program evaluation and review technique (PERT) are more appropriate to use. For repetitive-unit projects, where activities are repeated over the course of the project, such as, track housing and vertical construction, the line of balance (LOB) method is commonly used. Similarly, for linear projects such as highways, railroads, pipelines, etc., where both space and time are important for better management and control, the linear scheduling method (LSM) is particularly applicable (Yamin 2001). However, due to the fact that each construction project is unique, achieving all the planning objectives becomes quite challenging. In recent years, the department of transportation (DOT) has implemented a larger number of highway rehabilitation projects in virtually every state in the United States. Highway rehabilitation projects differ fundamentally from new highway construction projects in that they require an uninterrupted flow of traffic throughout both the duration and geometric length of the project. Work progress in a highway rehabilitation project is achieved either by providing an alternate bypass for the traffic or by providing appropriate traffic closure as required by the work progress. Although the use of an alternate bypass would be the ideal solution with regard to safety and work progress, it is usually limited to major reconstruction projects and not adopted for use in most rehabilitation projects. When planning and constructing a project without a separate bypass, the traffic has a direct influence on the work progress and the sequence of lane closures. Although most of the highway rehabilitation projects involve predominantly linear activities, application of traditional linear scheduling techniques are not practical to highway rehabilitation projects as the existing models are basically developed for a new construction project and do not consider traffic interference in the workzone (that is, both the interference caused by the public traffic to construction and that caused by the closed lane to the public traffic). This paper introduces a traffic closure integrated linear schedule (TCILS) technique that integrates associated traffic closure issues during work progress to the traditional linear scheduling.

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Linear Schedule Background

A significant effort has been invested by a number of researchers to introduce linear scheduling to the construction industry and to

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help build confidence and eventual acceptance of the method. Bafna (1991), Vorster et al. (1992), Harmelink and Rowings (1998), Mattila (1997), and Liu (1999) brought the LSM from a mere graphical tool to a more analytical and computational tool. Harris and Ioannou (1998) developed a method of scheduling by integration of various other LOB techniques into one generalized and simplified model, which was named the repetitive scheduling model (RSM). This model ensures continuous resource utilization and is applicable to both vertical and horizontal construction. Harris and Ioannou suggest that all linear projects, whether linear due to geometrical layout or linear due to repetitive use of unit network, can be scheduled using RSM, since all projects are repetitive in nature and the only difference is the type of representative unit plotted against time. There is, however, a fundamental difference between RSM and LSM. The RSM, like the LOB technique, schedules activities based on discrete and repetitive units, whereas, the LSM uses the whole length of activities and considers them as continuous. Harmelink (1995) elaborated on the linear scheduling method with additional analytical capability by developing a simple but effective algorithm that identifies both the time and place where activities are part of the controlling activity path (CAP). This is analogous to identifying which activities are on the critical path in the CPM. After the development of Harmelink LSM, a number of researchers have added additional enhancements. Mattila and Abraham (1998) proposed an algorithm to optimize resource usage in highway construction based on the CAP and rate float conceived by Harmelink LSM. Liu (1999) developed a resource allocation mechanism for the LSM. The linear construction planning model (LCPM) is another modification that schedules both continuous linear activities and discrete activities within a linear project (El-Sayegh 1998). Yamin (2001) added statistical capabilities to the LSM by analyzing the cumulative effect of productivity rate variability (CEPRV) on linear activities in a highway construction project. Efforts have also been made in the development of linear scheduling computer software. TransXcom (Vorster et al. 1992) is a linear scheduling software tool that represents a CPM network in linear scheduling format. PULSS (Harmelink and Yamin 2000) is another effort in software development with the analytical capability of LSM.

Linear scheduling has seen limited application within the construction industry. Network-based scheduling, such as CPM and PERT are still predominantly used for all types of construction projects. According to a survey conducted by Rowings and Rahbar (1992), none of the 36 responses from the state DOTs in the United States (US) used linear scheduling or LOB technology to schedule highway projects. Another survey by Herbsman and Glagola (1999) showed that among 37 US DOT respondents, 65% were not familiar with the LSM; 27% were somewhat familiar with the LSM; and only 8% were very familiar with the LSM. This indicates that construction companies and government agencies are still far from adopting and applying the LSM to actual highway construction. Typically, DOTs and highway construction contractors rely on the traditional Gantt chart and CPM scheduling methods. These techniques do not specially address the issues related to traffic and idle time for equipment. Due to these shortcomings, the Gantt chart and CPM are unable to provide meaningful information related to the timing and duration of traffic closures. This clearly illustrates the need to develop advanced scheduling methods and techniques that specifically address these issues.

Methodology for the TCILS

TCILS adds an important dimension in the linear scheduling technique by integrating the associated traffic closure issues with work progress by generating an enhanced visual and graphical schedule for construction activities and the associated traffic closures. The development of TCILS for highway rehabilitation projects consists of five phases: Phase I—workzone and construction sequence; Phase II—preliminary linear schedule (PLS); Phase III—least closure-time linear schedule (LCLS) on PLS; Phase IV—traffic closure setup and removal on LCLS; and Phase V—final traffic closure integrated linear schedule (TCILS). Each of these steps is illustrated in detail in the subsequent sections. The methodology of application of TCILS is demonstrated through a sample highway rehabilitation project on a one-way two-lane roadway.

Phase I—Workzone and Construction Sequence

Highway rehabilitation projects may vary in length from a few miles to tens of miles. The construction must be performed with complete assurance of an uninterrupted flow of traffic throughout the length of the project. Since the progress of work takes place linearly with specific production rates from one station to another, it would be inappropriate to have a full-length lane closure for mid- or long-length projects. In order to avoid unnecessarily long traffic closures, the total length of a highway rehabilitation project must be divided into a number of workzones. These workzones and related traffic closures are planned to provide an adequate traffic flow, as well as the smooth operation of construction activities. Workzone identification and sequencing provides the foundation for the TCILS.

Traffic closure in any workzone can be measured in terms of "mile day" by multiplying the length by the duration of closure for the workzone, which is actually an area within the linear schedule. A summation area (mile day) for all the workzones determines the traffic closure for the entire project. Since traffic closure is dependent on the construction activities, a set of workzones and a construction sequence can be determined, thus, producing minimal traffic closure (mile day) for any project. Optimization of workzones, however, is beyond the scope of this paper, and, therefore, a predetermined set of workzones and construction sequences are used to illustrate the TCILS. For the example project, the total project length (L) is assumed to be divided into three workzones of equal lengths. The construction sequence is planned to follow sequentially from workzone 1 through workzone 3 on the closed lane before it is switched to the other lane.

Phase II—PLS

The construction of a linear schedule is generally based on the following parameters: (1) activity breakdown or activity identification; (2) activity sequence; (3) buffer time and/or buffer distance between two consecutive activities; and (4) production rates. Activities are usually identified by subdividing the entire project into a number of tasks that consume resources, i.e., material, labor, equipment, money, and time. Activity sequence leads to the logical relationships between the activities, and a single predecessor/successor relationship is assumed between any two activities. Buffer time or/and buffer distance between the con-

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secutive activities are actually the least time (LT) or least distance (LD) that have to be provided at all times and locations between activities. The example project assumes that the three continuous activities performed in sequential order are separated by minimum buffer time of LT_{AB} between activities A and B, and LT_{BC} between activities B and C.

Production Rate. In order to accomplish the work, each activity requires the application of resources. Only a specific amount of work can be accomplished for any activity using specific resources. The production rate for any activity is the amount of work that can be accomplished by the resources in a given period of time. In highway projects, the amount of work is usually measured by the distance covered between stationing. Mathematically, this is expressed as

$$R_A = (S_f - S_s)/(T_f - T_s) \tag{1}$$

where R_A=production rate of activity A, expressed in stations per day or miles per day; S_s and S_f=start and finish station for the activity A; and T_s and T_f=corresponding start and finish times. $1/R_A$, the reciprocal of activity production rate, gives the slope of activity A in a linear schedule with location in the abscissa and time in ordinate. An activity with a higher activity production rate will have a flatter slope, and activities with lower rates of production will have a steeper slope. However, it should be noted that the measure of progress is in terms of miles of station along the roadway, and the actual quantity may vary along the course of the project.

Construction of the PLS. Once the activity data (activity identification, activity sequence, buffer time and/or buffer distance, and production rates) have been determined, the actual construction of the linear schedule can be performed on a two-dimensional graph with location (or distance) on the x-axis and time on the y-axis. In their RSM model, Harris and Ioannou (1998) developed a systematic method of constructing linear schedules for different kinds of logical relationships between consecutive repetitive activities with consideration of continuous utilization of resources for repetitive activities. Due to the geometrical linearity of a highway project and the concept of buffer between activities, highway rehabilitation projects do not typically fit in the RSM model. However, the concept of the construction of a schedule with respect to relative convergence or divergence between two consecutive linear activities based on their production rates can still be utilized to construct the preliminary schedule. Thus, a PLS is constructed for the major linear activities in the project, assuming the activities will progress continuously throughout the entire length of the project.

The construction of the schedule begins with the first (i.e., independent or base) activity and progresses by adding the dependent activities in the predetermined logical sequence. Since the activity production rate is assumed to be uniform from the start to the end of the project, plotting any activity using the linear scheduling format only requires two points (beginning and end) and is connected with a straight line.

To illustrate this process, let X be an independent activity or a base activity with a constant activity production rate of R_x in a highway project of length L. The beginning and end times required to plot the activity on the linear schedule are given by the expressions

$$X_b = K \tag{2a}$$

$$X_e = K + (1/R_x)^*L \tag{2b}$$

where K is a constant, i.e., the start time for the base activity (K=0 for the first activity); "b" represents beginning; and "e" represents end.

Subsequent activities are plotted dependent on the relationship of its activity production rate and that of the base activity. For example, let Y be any dependent activity with either a predecessor or successor relationship with the base activity X. If R_x and R_y=respective production rates for activities X and Y, then the beginning and end points for activity Y are dependent on the following two conditions: (1) diverging activities; and (2) converging activities, as explained below.

Condition I: Diverging Activities. When the base activity with a greater production rate precedes the dependent activity, or the base activity with a lesser production rate succeeds the dependent activity, the two lines tend to diverge as the project progresses. This causes the control point to occur at time LT from the base activity at the beginning station. The respective beginning (Y_b) and the ending (Y_e) time for the activity Y are expressed by Eqs. (3a) and (3b), as given below

$$Y_b = X_b \pm \mathrm{LT}_{xy} \tag{3a}$$

where "+" is used if Y succeeds base activity X and "−" is used if Y precedes X

$$Y_e = Y_b + (1/R_y)^*L \tag{3b}$$

Condition II: Converging Activities. When the base activity with a lesser production rate precedes the dependent activity or the base activity with a greater production rate succeeds the dependent activity, the two lines tend to converge as the project progresses. This causes the control point to occur at time LT from the base activity at the ending station. The expressions for the ending and the beginning times for the activity Y are given by

$$Y_e = X_e \pm \mathrm{LT}_{xy} \tag{4a}$$

where "+" is used if Y succeeds the base activity X and "−" is used if Y precedes X

$$Y_b = Y_e - (1/R_y)^*L \tag{4b}$$

Determination of Preliminary Controlling Activity Path. After all the major activities are plotted in the linear schedule, the preliminary controlling activity path (PCAP) can be determined by performing the upward and downward passes, as per the Harmelink LSM. The upward pass identifies the potentially controlling segments and the downward pass determines the actual controlling and noncontrolling activity segments and links, along with the CAP for the project. However, not all the segments passing through the CAP are necessarily the critical segments. There can be both critical and noncritical segments in the CAP identified after performing the upward and downward passes. Any controlling segment in the CAP that appears with a new controlling link, developed during the downward pass, is usually a noncritical segment. The thick line in Fig. 1 represents the PCAP for the example project.

Float Region. Float is a term commonly used in CPM scheduling to describe the amount of time that the start or the duration

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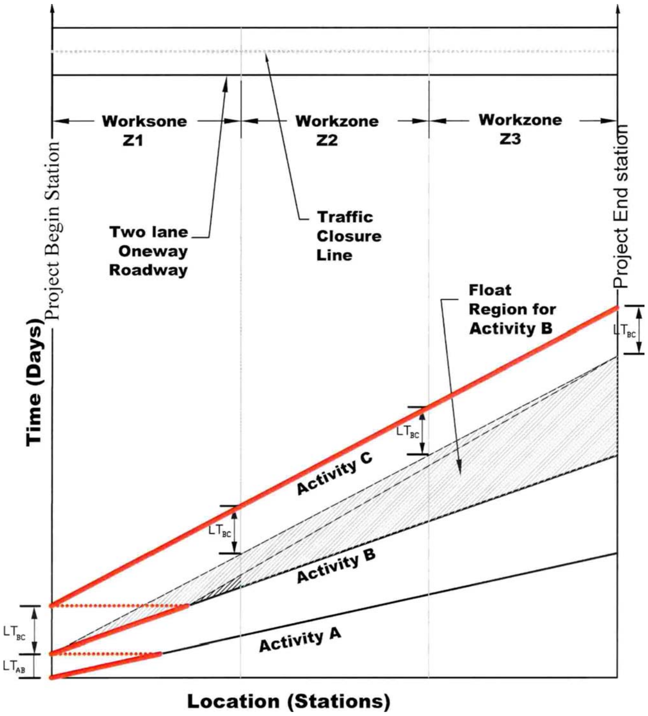

Fig. 1. Preliminary linear schedule (PLS) with PCAP and float region $R_A > R_B > R_C$

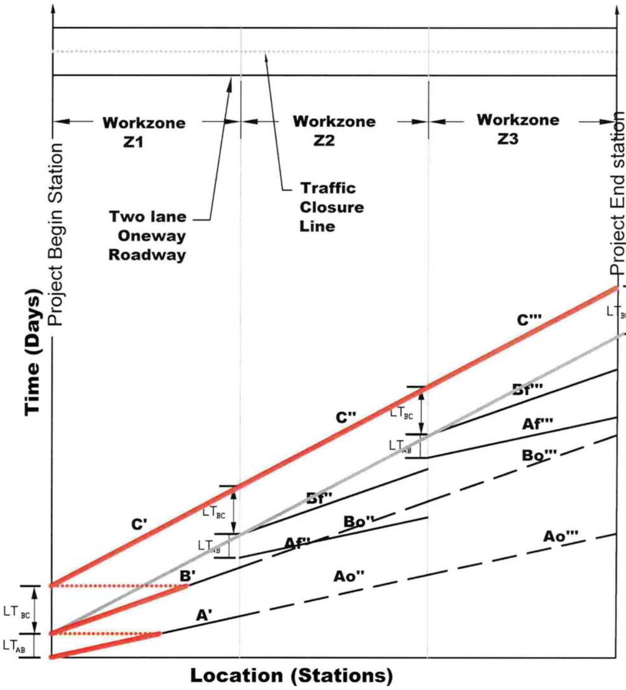

Fig. 2. Initial and final positions of noncontrolling segments $R_A > R_B > R_C$

of noncritical activity can be extended without the activity becoming critical. The Harmelink LSM uses the term "rate float" to define the amount of time that the production rate of a noncontrolling activity segment can be decreased before it becomes controlling. However, the use of rate float is rarely used in actual practice since most activities are assigned with a set of crew and/or other resources. The float can best be utilized by actually delaying the start and end date for the noncritical segment by moving the segment of activity within the float region. Technically, the float region is the area in the linear schedule in which the noncritical activity can be moved without affecting the total project duration as shown by the shaded region in Fig. 1.

Phase III—LCLS on PLS

The linear schedule provides a graphical and visual environment to align various segments of linear activities based on the objectives of the project. The basic objective is to achieve a minimum time of traffic closure throughout the length of the project by adjusting (moving) the noncontrolling segments of an activity within the available float region. A technique similar to the Mattila and Abraham (1998) work is applied for the segment movement. The movement takes place toward the critical segment contingent on the available float. The identification of PCAP and float regions allows the planner to visually identify the segment of activities that may or may not undergo movement. Only the noncritical segment of PCAP may be moved. Appropriate labeling of segments can be used to distinguish segments with or without potential movement. In the example project, the sections of activities that do not undergo movement are labeled as A', A'', A''', B', B'', B''' and so on with respect to the workzone sections and those with potential movement are labeled with subscript "o" and "f" to designate the "original" and "final" position of the section of activity as shown in Fig. 2.

The movement of any section of activity is based on Eq. (3*a*), (3*b*), (4*a*), and (4*b*). In each workzone, the activity with a critical segment becomes the base or independent activity and the activity immediately preceding/succeeding it will be the dependent activity, which will take a new position according to the corresponding conditional expressions. When there are a number of noncontrolling activities in a given workzone, then the movements of the activities take place in order, starting from the one immediately preceding/succeeding the controlling segment. When an adjacent activity is moved, it then becomes the base activity for the movement of the subsequent activities within the workzone.

In Fig. 2, the PCAP is indicated by the bold lines. The PCAP passes through the activity sections labeled as A', B', C', C'', and C'''. The rest of the activity sections do not contain any critical activity segments and are labeled as A''_o, A'''_o, B''_o, and B'''_o, which indicate the original positions of schedule. As described in the preceding paragraph, the movement of these activity sections begins at the one immediately preceding/succeeding the controlling segment in that section. Since all the activities in workzone 1 (Z1) contain critical activity segments, they all remain in their original positions and are not moved. In workzone 2 (Z2), the activity B''_o will be the first to move in the sequence. The movement is calculated from Eqs. (3*a*) and (3*b*) using the critical section of activity C'' as a base activity. The beginning and end time for the final position, i.e., B''_f are

$$B''_b = C''_b - \mathrm{LT}_{bc} \tag{5a}$$

$$B''_e = B''_b + (1/R_b)^* L_2 \tag{5b}$$

Once activity B attains its final position, the activity immediately preceding/succeeding B in workzone 2, i.e., activity A''_o, can undergo movement taking the final position of activity B (B''_f) as the base activity. A''_f=final position of activity A in workzone 2, as shown in Fig. 2. Similar movements take place for the noncritical sections of activities in workzone 3 and attain the final positions

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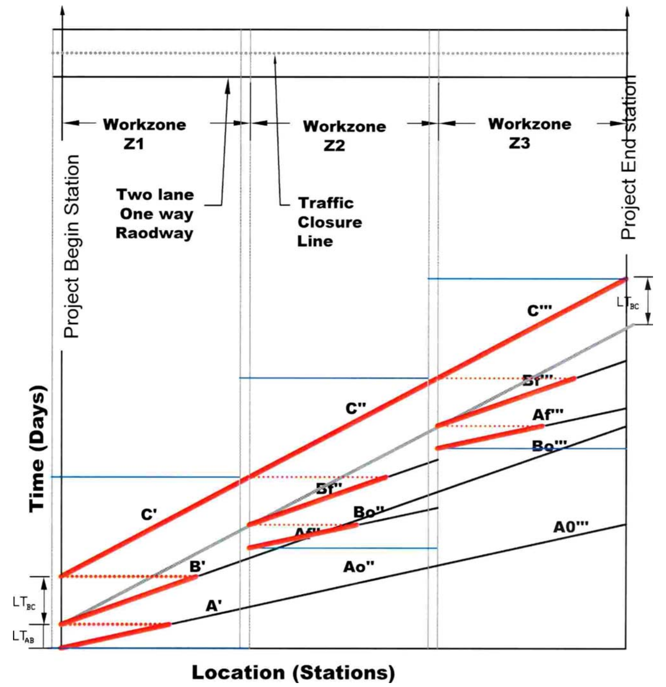

Fig. 3. Schedule for traffic closure setup and removal $R_A > R_B > R_C$

of B_f''' and A_f''' from their original positions B_o''' and A_o'''.

A schedule with minimal time of traffic closure can be generated after moving all of the noncritical sections of activities in all workzones of the project. However, this changes the controlling activity path of the project, typically resulting in the addition of more critical activity segments. The new CAP for the project will be determined by performing upward and downward passes on each workzone after all the activities attain their final positions as shown in Fig. 3.

Phase IV—Traffic Closure Setup and Removal on LCLS

Typically, in a highway rehabilitation project, the traffic has to be closed or diverted (i.e., lane closure), before any construction activities can begin. Once the schedule of minimum time of traffic closure is completed, the horizontal bar (HB) activities "traffic closure setup" and "traffic closure removal" can be visually plotted in the linear schedule. Since the closure has to be in place before any activity can begin at any location, the time traffic closure setup activity takes place at the beginning of the first construction activity for a workzone. A certain length of taper, before the start of actual workzone, has to be provided to divert the traffic away from the closed lane. The length of the first HB for traffic closure setup will be one taper length longer than the length of the first workzone section. The remaining traffic closure setup will be at the time of the start of the first construction activity and will cover the length of the workzone. Likewise, the traffic closure can be taken down as soon as the last activity reaches the end of the workzone for the length other than the taper length required for the next workzone. Traffic closure removal commences when the last activity reaches the end of the workzone.

Phase V—Final TCILS

In a highway rehabilitation project, work that occurs across the entire width of the highway has to run more than once at any station since at least one lane of traffic must be open at all times. Due to the constraint of a two-dimensional graphical format of linear scheduling, it cannot distinguish a construction process where the same activity takes place at different cross-components (such as: right lane, left lane, right or left shoulder, right or left ditches, etc.) at the same station of a highway at different times. The distinction can be visualized through the use of shadings or colors to relate the schedule with the corresponding cross-component of the roadway.

In the example project, a one-way two-lane highway rehabilitation project, all three activities (A, B, and C) have to occur twice at any location to perform the work on each side of the traffic closure. It is assumed that the quantity (volume) of work on either side of the closure is equal for all three activities, and the activity production rate (slope), being in terms of unit distance per unit time, will remain unchanged. The construction of the schedule on the other side proceeds after the identification of the independent activity and its start time, which may be limited by the resources available for the project.

Resource Constraint TCILS. If only one set of resources is available for an activity, then the activity can take place at only one location at any time, although the physical constraint does not restrict it to occur at more than one location. In this case, the independent activity is usually the activity with the least production rate. In the example project, the activity C becomes the independent activity and its start time, on the second closure in workzone 1, controls the schedule for all other activities. The earliest possible start time for C on the second closure is its finish time for the last workzone 3 in the first closure. The two controlling points are marked as ending control point (CP_e) and beginning control point (CP_b) in the linear schedule. After the beginning control point of any activity is determined, the schedule for the rest of the activity can be created as illustrated in Fig. 4.

Physical Constraint TCILS. In this case, the construction of the schedule assumes only the physical constraints and no resource constraints. If there are no limitations on resources, the construction activities can be carried out on the second side of the closure at any workzone, as soon as the work progress on the first side has reached at least a taper length farther on the next workzone. In this case, the same activities take place at different locations at the same time and, thus, require additional sets of resources to carry out the activities. The independent activity is usually the first activity at any workzone. The control point, i.e., the earliest start time of the independent (first) activity, is the time when the final activity has progressed by one taper length in the following workzone. For the example project, the activity A starts on the second side of the closure at the time when the progress of activity C on the first side reaches a taper distance away on the next workzone as shown in Fig. 5. As the lengths of all workzones are equal, the control point to start activity A occurs at the beginning of all three workzones. For varying lengths, the control point would occur at the beginning of the longest workzone. The beginning control point provides the base to construct the linear schedule for all the activities on the second side of the closure. Once the control points are identified, the construction of the linear schedule on the second side of closure can be done follow-

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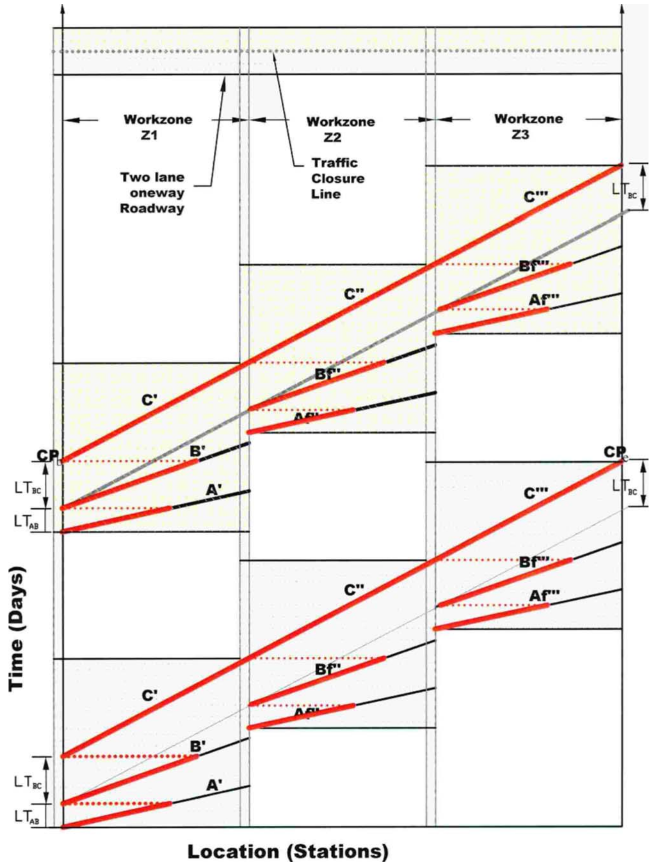

Fig. 4. Resource constraint TCILS $R_A > R_B > R_C$

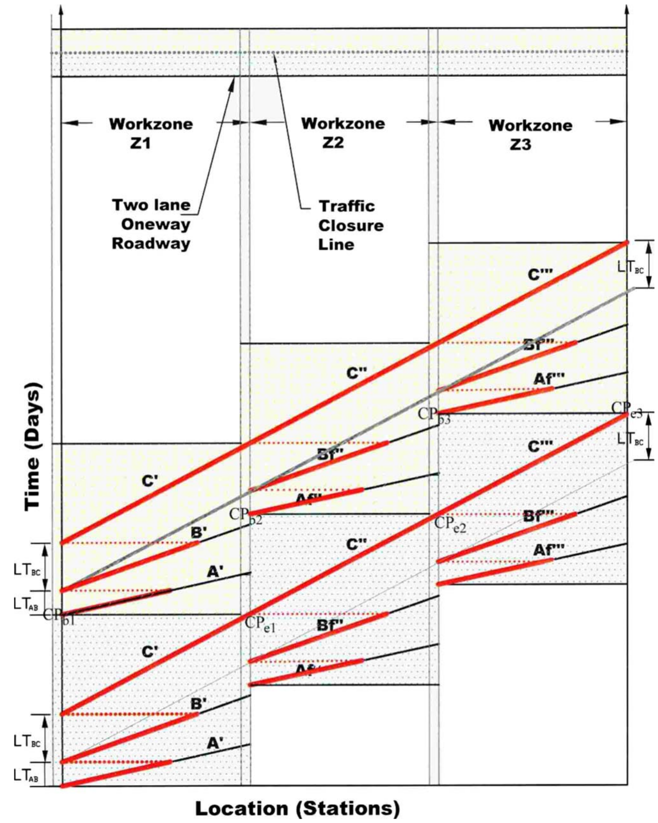

Fig. 5. Physical constraint TCILS $R_A > R_B > R_C$

ing similar procedures.

Once the linear schedule for all activities, including the traffic closure setup and removal, is plotted, shades or colors can be used between the two horizontal-bar activities (for traffic closure setup and removal) to generate the complete TCILS. The use of shades and colors in TCILS provides the location and time of traffic closure and also allows a clear distinction between activities occurring at different cross-components at the same station.

The methodology presented above illustrates the development of TCILS for a highway rehabilitation example project consisting of three continuous linear activities for only one case ($R_A > R_B > R_C$). However, the methodology holds good for all other cases ($R_A > R_B$ and $R_B < R_C$, $R_A < R_B$ and $R_B > R_C$, and $R_A < R_B < R_C$) (Sharma 2005). TCILS generates a single schedule for construction activities and the associated traffic closures, which becomes especially attractive for highway rehabilitation projects. A sample project is used to demonstrate the applicability of the TCILS to an actual highway rehabilitation project and is presented below.

Sample Project—Application of the TCILS

The concrete pavement rehabilitation (CPR) project is a typical example of a highway rehabilitation project. This project mainly utilizes the dowel bar retrofit (DBR) technique to rehabilitate jointed concrete pavements where faulting is a major problem, but otherwise the pavement surface is in good condition. Slots are cut into the roadway over the joints, and dowel bars are set in the slots at midpavement depth. The slots are then back-filled with a patch material. Later, the pavement is diamond ground to produce an even surface between pavement sections. Finally, all the joints and random cracks are sealed. The objective of the CPR project, in addition to a smooth surface, is to extend the service life of the existing pavement by 10–15 years, through the increased load transfer capability provided by the DBR. With the realization of the importance and cost effectiveness of DBR techniques, the implementation of CPR projects on existing concrete pavement has increased significantly in recent years. This increase has had a significant impact on the planning and scheduling of CPR projects. For the successful implementation of such projects, it is critical for DOTs and constructors to know when and how long a closure will remain at any location in the project. Due to the lack of adequate tools that would easily generate or obtain information related to traffic closures, both management and labor may be unaware of which lane will be closed until the actual work has reached a particular location. This may disrupt the overall work flow and affect actual work progress resulting in idle time for equipment and a possible delay in the completion of the project.

Project Overview

The North Dakota (ND) DOT Valley City District implemented a CPR project located in Barnes County, ND on I-94 east bound from Eckelson to Oakes interchanges in the summer of 2004. The project had a gross length of 20.096 km (12.487 miles) from station 239+98 to station 918+00. The net length of the project excludes two relatively new pavement sections, one at Eckelson Lake (0.950 km) and other at Hobart Lake (1.094 km) that were reconstructed in 1999. The Interstate 94 eastbound roadway consists of two 3.659 m (12 ft) wide pavement lanes, a 3.049 m

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(10 ft) right shoulder, and a 1.220 m (4 ft) left shoulder giving the total width of 11.585 m (38 ft). The majority of this section of the pavement was originally constructed in 1984 and consists of undoweled concrete panels 3.659 m (12 ft) wide, 254 mm (10 in.) thick with 1:6 skewed joints spaced at an average distance of 4.573 m (15 ft).

Major Activities

The major project tasks were broken down into a number of activities in order to represent them in a linear scheduling graphical format. The identification of an activity was done with consideration to resource utilization and the process of construction operation. The major tasks involved in the projects were: (1) pavement reconstruction; (2) DBR; (3) full depth and spall repair; (4) bridge repair work; (5) pavement grinding; and (6) joint and crack resealing.

The major tasks were grouped into three categories: linear, block, and bar. The activities identified as linear activities were: (1) slot saw (SS); (2) jack hammer (JH); (3) pour slots (PS); (4) pavement grinding (PG); and (5) joint sealing (JS). The first three activities occurred only on the right lane of the two-lane roadway, whereas, the PG and JS occur across the entire width of pavement. As one of the lanes has to be opened for traffic, these activities have to be run at least twice at any station. As a result, each of these activities has to be divided into two activities, i.e., for example, activity PG becomes: pavement grinding on left side (PG-L) and pavement grinding on right side (PG-R). Similarly, the activities identified as block activities for this project included: (1) new pavement construction (NPC); (2) bypass work (BPW); (3) full and partial depth repair on right side (F&PD-R); and (4) full and partial depth repair on left side (F&PD-L). Bar activities in this project included: (1) bridge repair on right side (BR-R); and (2) bridge repair on left side (BR-L)

As-Built Linear Schedule

The as-built linear schedule was constructed in order to obtain both temporal and spatial visualization of actual activity progress. A schematic "plan view" of the project is shown at the top of the schedule. Fig. 6 shows the as-built linear schedule for the entire project. This gives the overall picture of actual progress of various activities with respect to time and space. It should be noted that this project was not planned or constructed using linear scheduling. The as-built linear schedule was constructed once the project was completed using actual project data. The as-built schedule reveals that the construction operation was not planned to progress continuously from station to station despite the linear nature of the project. There are numerous breaks in the work progress creating idle time for equipment. In addition, project personnel were unaware of the advance information on the actual lengths and locations of traffic closures. These shortcomings observed in the sample project could be addressed through the use of TCILS as explained in the following sections.

Application of TCILS

The three basic parameters (1) activity identification; (2) interrelationship among the activities or the logic; and (3) productivity or the activity production rate, required to construct TCILS, are obtained from the actual project data. The major activities and their interrelationships to construct the TCILS are the same as those used in the actual project and the as-built schedule. The actual work-progress data are used to determine the production rates of the linear activities involved in the project. Daily work production data associated with the normal work environment were used to obtain the activity-production rates for the proposed TCILS.

After the data related to the basic parameters were ready, the proposed TCILS for the project was constructed following the steps presented previously. The entire length of the project was divided into five workzones based on visual inspection of the project. Workzone Z1 consists of pavement reconstruction where a separate bypass is provided for traffic. The remaining workzones Z2 through Z5 have CPR activities, where the construction operation is planned to be progressed continuously on the right side of the closure [right lane and 3.049 m (10 ft) right shoulder] before it is switched to the opposite side. Once all the activities are completed on the initial side, they will continue on the opposite side, which consists of the left lane and the 4-ft left shoulder. Although a very small portion of Z1 at the beginning of the projects also contained some CPR work, this has not been considered in the TCILS. The assumption is that the effect of this CPR work is insignificant in the overall project schedule. Furthermore, the objective of this study to demonstrate the application of the proposed scheduling methodology is not compromised by excluding this small portion of the project.

The development of TCILS proceeds with the construction of the PLS for construction operations on the right side of the pavement centerline for the net length (excluding the "no-work" zones) in workzones Z2 to Z5. The activity segments are moved appropriately within the allowable float region to produce the LCLS. Once the least traffic closure linear schedule for one side of the pavement centerline is completed, the schedule for the other side can be started from a control point. The control point for a resource-constrained schedule is governed by the slowest controlling activity, which in this case is PG. The remaining activities are then scheduled with respect to this activity for all workzones. The horizontal bar activity for traffic closure setup and removal are then inserted. Shadings or colors are applied in the schedule that differentiates an activity that occurred at the same station but at different times and on different sides of the centerline.

Fig. 7 shows the final TCILS for the project. In general, crossing of lines in a linear schedule exhibits the temporal and spatial conflict between the activities. The presence of intersecting activities also contradicts in the determination of CAP. Although the bar activities (bridge repair) in the TCILS for the sample project, are shown to intersect other linear activities, there is no conflict between them. The linear activities do not actually occur on the bridges; they simply skip the bridges on their course of progress, which could not be shown graphically due to the limitation of scale. The crossings do not reflect a conflict in the sample project. Further, the contradiction with the Harmelink method of determining CAP can be resolved by performing the upward and downward passes prior to introducing the bar activities.

Findings and Future Research

Since network-based schedules do not necessarily consider the space (location) of an activity at a specific point in time, it is very difficult to adequately manage and control the project. The appli-

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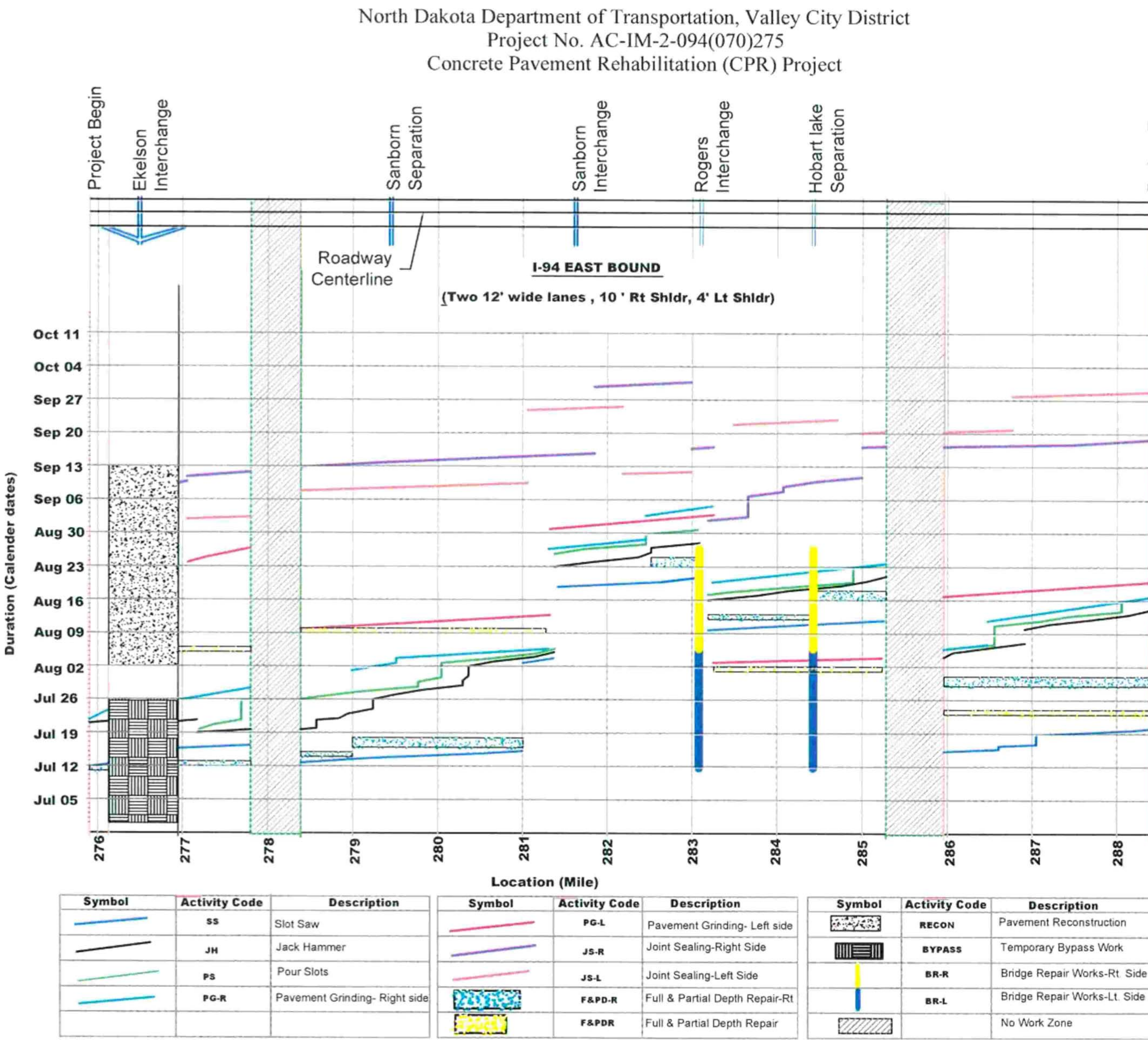

Fig. 6. As-built linear schedule

cation sample showed that the TCILS, on the other hand, provides a two-dimensional graphical representation of time and space that can be utilized to address traffic regulation issues, as well as actual construction activity during a highway rehabilitation project. The TCILS is mainly a graphical tool, but it is also analytically robust. The development of TCILS follows a systematic procedure that is based on logical and mathematical expressions and adds managing and controlling capabilities in the project through the identification of a CAP. It properly addresses the issues related to traffic that help identify and avoid the conflicts with traffic closure and work progress. This also helps reduce unwanted idle time for plants and equipment involved in construction, which may result in a reduction in the project duration. The model provides, at a glance, an overview of the complete traffic-closing pattern for the entire project. The use of TCILS can allow users to appropriately plan and schedule the traffic-closure issues in and around the project area.

This research represents the initial efforts at applying the linear scheduling technique to highway rehabilitation projects by integrating the traffic closures. It only develops the preliminary functions and lays a foundation for the development of additional features and applications in order to become a complete project management tool. Improvements to a wider range of applications can be achieved by reducing the underlying assumptions of the proposed TCILS. Further study is needed to add cost and resource-loading features and to expand the model to cover multiple traffic-closing patterns for multilane highway rehabilitation projects.

In addition, in this study, the workzones were assumed to be determined based on a visual inspection of the project, and do not consider the resulting traffic closure. In addition to production rates and project logic, the traffic closure is also dependent on the lengths and number of workzones identified for a rehabilitation project. A logical extension would be the development of an op-

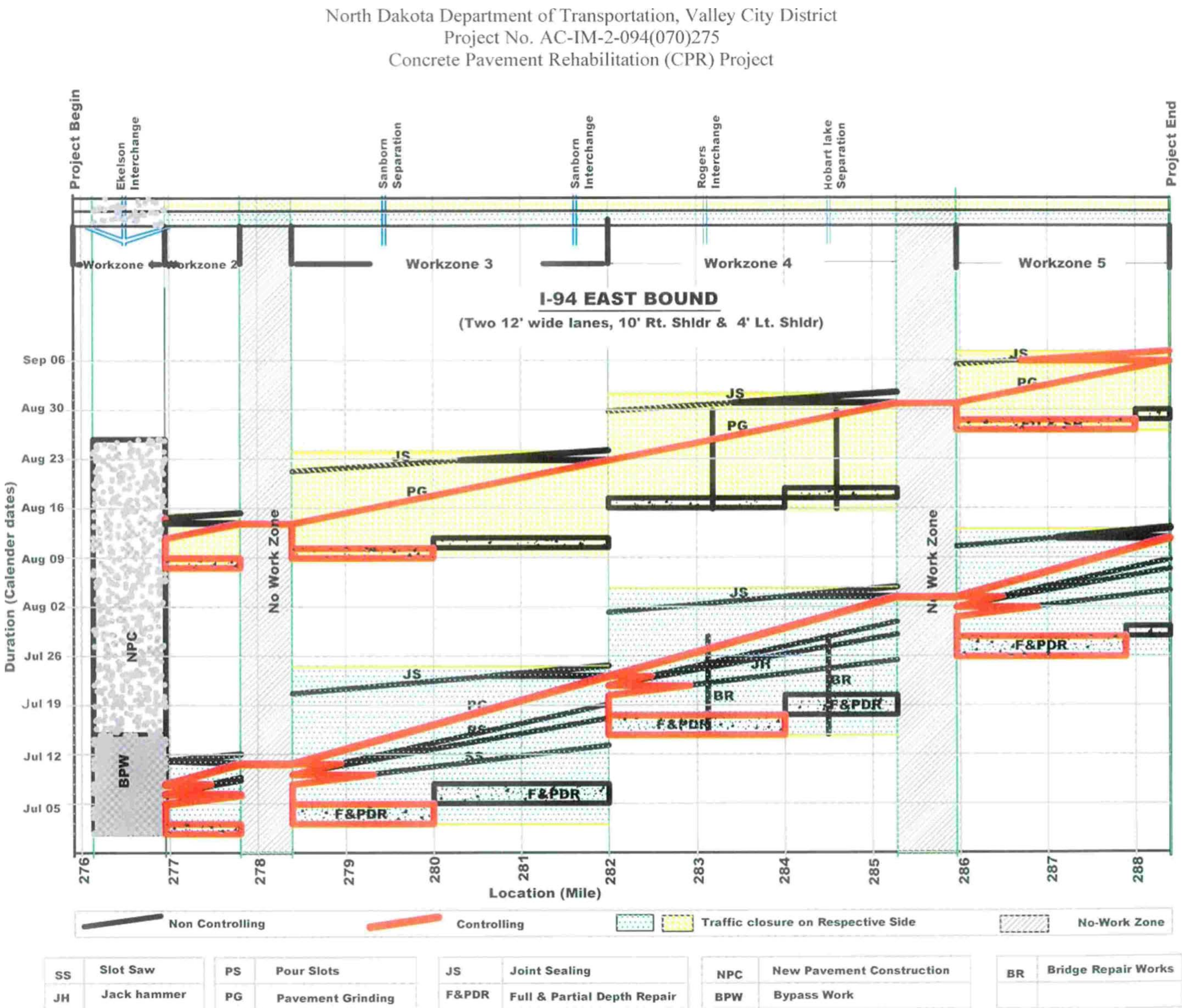

Fig. 7. Traffic closure integrated linear schedule

timization technique integrated to the proposed TCILS that produces the least traffic closures in a highway rehabilitation project.

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