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The *Journal of Construction Education* (ISSN 1522 8150) was founded in 1996 by the Associated Schools of Construction, an association of 105 international colleges and universities with construction education programs. The purpose of the *Journal* is to provide an important process necessary for the preservation and dissemination of manuscripts that report, synthesize, review, or analyze scholarly inquiry. The *Journal* is an important way of our focusing international attention on and contributing to the understanding of the issues, problems, and research associated with construction education and training. The recognition of scholarly work within the realms of curriculum information, contemporary educational practices, educational research and instructional application development within construction departments, schools and colleges, and industry are the reasons for the *Journal's* existence. The *Journal's* mission is to provide construction educators and practitioners with access to information, ideas, and materials for improving and updating their understanding of construction education and training. It is also intended to help its constituency become more effective in developing the talents of learners within construction programs. This *Journal* is not only a living textbook of construction education, but also a perpetual and dependable learning source for construction professionals whether they are within academia or within industry. The *Journal* will be published tri-annually (Spring, Summer, and Fall issues). The divisions of the *Journal* include invited and editorially reviewed Book Reviews and Teaching Profiles, and blind peer reviewed Educational Practice and Research Manuscripts.

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Construction Ph.D. Level Education

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A Ph.D. program in Construction Management requires a mastery of academics and practice in the broad area of Management and Science. It involves in-depth knowledge of specific areas of construction that involve skills in problem solving and the analysis of information; and the capacity to make original contributions to the field. To develop these abilities, a Ph.D. program in Construction Management has the following components: 1) Education in the various fields of Construction Management, 2) Detailed knowledge of a specialty or research concentration, and 3) A significant original contribution to the field. This corresponds to a layered model of graduate studies where students begin by developing a broad base of knowledge, and, building on that, progressively deeper understanding and skill in fields of increasing specialization: These principles: 1) Focus on preparing students for original research by developing a broad foundation followed by increasing specialization, and 2) Guide the design of a Ph.D. program in Construction Management. While a Ph.D. in Construction Management offers a structured curriculum to develop research capabilities and skills, the program is also flexible, in recognition that each individual student's program should be unique.

Key Words: Graduate Education, Ph.D., Curriculum, Competencies, Requirements

Introduction

A Ph.D. is a research degree. We believe those who receive a Ph.D. should be talented and enthusiastic organizational scholars. They should be able to critically evaluate existing research, translate and disseminate research knowledge to their students and their communities, and conduct their own original research adding to what we know and what we do in the construction management discipline. Therefore, students whose major field is construction management should always receive research-oriented training.

A primary form of that training could occur in one-to-one working relationships. From their first semester/quarter in a Ph.D. program, students should be encouraged to work closely with faculty members on current research projects, from which jointly authored papers are submitted and published in the field's top journals.

A program should also have high expectations that students should learn from and do well in their coursework. A Ph.D. program in construction management should require 18 semester/27 quarter hours of classes in the Construction Management major and 12 semester/18 quarter hours in research methods. Students should find that their content knowledge helps them to apply and crystallize what they learn about research methods. Likewise, programs should expect research methods courses to help students make better, more informed conclusions about existing construction management theory and research.

Finally, a Ph.D. program should also prepare students to excel in teaching. Although students should probably not be classroom instructors until after they pass one or more of their comprehensive exams, each student should be linked with individual faculty members as "teaching mentors." Through this mentoring program, students should learn how to put together a course syllabus, prepare and deliver lectures, create and grade assignments, construct and evaluate tests, and track student progress.

Description

A Ph.D. program should be student-centered. It is for this reason, that a program should be kept deliberately small - maintaining close to a 2:1 ratio of students to faculty. A Ph.D. program in Construction Management should offer a flexible set of courses to fit with student interests. It should allow exceptionally qualified students the opportunity to attend part-time and work part time. The Ph.D. student should be encouraged to follow his or her own research interests rather than be compelled to follow a particular faculty member's.

The maintenance of a construction management academic community is the mutual responsibility of students and faculty. Doctoral students are collaborators in the academic research enterprise. In addition to its formal curriculum and requirements, the following shared values and expectations should guide a Construction Management Ph.D. program.

The University is an open environment, not an environment for developing private work. Research work is measured by its impact on the broader scholarly community; therefore, without publication and dissemination, the research work would have limited impact. Students should maintain web pages to keep the Construction Management community, and as appropriate, the wider scholarly community, aware of their activities. Whenever possible, research papers should be distributed through technical reports and web publication. When it reaches professional quality, students should actively disseminate their research results by publication in the scholarly and scientific literature and presentation at the leading research conferences.

A Construction Management program is a community in which students participate by attending seminars and talks, and by presenting their own work to the community, as appropriate. Such activities extend students' and faculty's' understanding, and prepare students for job talks, for conference presentations, and full participation in the larger research community.

As new members of a profession or discipline, doctoral students participate in creating a sense of community through service to the School and beyond by, for example, serving on Committees, giving feedback to other students about their work, and helping coordinate Construction Management events.

Mentoring and apprenticeship is at the heart of the Construction Management Ph.D. learning process. Each student shall meet regularly with his or her academic Advisor. Weekly meetings with the Advisor are possible, and often typical.

Students should be involved in the world of research from the day they enter the Construction Management Program, and the admissions process should center on the quality and focus of an applicant's research interests. The life of the researcher is a continuous process of seeking new ideas, finishing tangible research products, and presenting them to others. Of course, these results should vary depending on the student's interests and stage of preparation.

Research is largely a collaborative process. Students are expected to actively engage in collaboration with faculty and fellow students, and to develop collaborative skills. All students of the Construction Management Ph.D. program are expected to maintain the highest standards of intellectual integrity and ethics. This includes respect for other researchers, full intellectual honesty in reporting on one's own work, correctly citing prior work, adhering to appropriate standards for research, presenting information on published experimental results, and avoiding conflict of interest or the appearance of conflict of interest.

Competencies

The mastery of a set of skills and competencies needed for success in Construction Management disciplines should be required. Normally students should develop the following vital skills through coursework and industry experience.

- The ability to design and implement research projects, including gathering, analyzing, and interpreting qualitative and quantitative data, including statistical data.
- The ability to clearly express oneself in scholarly, professional or scientific publications and in oral presentations.
- The ability to critically read and assess research.
- The ability to use and program computers at a level necessary for academic success.
- A program should take these competencies seriously, and, as discussed below, students are required to demonstrate this competency requirement as part of the Preliminary Exam process.

The Advisor and the Advisory Committee

On entering the program, each student should be assigned a temporary faculty Advisor. The Graduate Advisor reviews the breadth and disciplinary composition of the student's program of study. The Advisor should help the student design his or her coursework, and certify that the student has mastered the core set of competencies outlined above. Within the first two years, the student should choose a permanent faculty Advisor.

Monitoring Student Progress

Guidance by the Advisor is intended to provide students with feedback and expertise necessary for making normal progress towards the Ph.D. degree. Each semester/quarter, each student should prepare a statement describing his or her program and its direction, accomplishments for the current semester/quarter, and goals for the coming semester/quarter. The Advisor should review these reports, discuss students' progress with the student, and prepare a letter for each student reporting on what the faculty sees as the significance of the student's accomplishments and goals.

If a student is not making satisfactory progress, the Advisor should make specific recommendations to help the student return to good standing as part of the semiannual review. The quantitative standards should be:

- A 3.5 cumulative grade point average across all Graduate courses taken.
- Construction Management courses must be taken for credit with a cumulative 3.5 GPA in all Construction Management courses.
- Students may not accumulate more than one incomplete at a time, other than for reasons of illness or emergency (requiring written notification of the Graduate Advisor).

The student's Advisor should define qualitative standards such as "normal progress towards the degree," in writing each semester/quarter. The normative goal of the program is that students should complete the preliminary exam requirement in 8 semesters/12 quarters, and the Ph.D. dissertation in 12 semesters/18 quarters.

Failure to make normal progress towards the degree, as measured by these standards and processes, would result in a request to the Graduate Division that the student be placed on probation. The probation letter would state specific requirements that must be met for the student to return to good standing, and a reasonable timetable for meeting these requirements. Failure to meet these requirements in due time should result in dismissal from the program.

Coursework and the Preliminary Exam

In the first years of coursework, students gain a broad background in Construction Management, and then acquire an in-depth understanding of one Major and two Minor disciplines or research areas. The following principles and structures frame an educational process that meets most students' needs most of the time. In practice, these principles should be flexible, and most rules may be waived with the approval of the student's Advisor and interested faculty.

Because Construction Management is an inherently interdisciplinary field, the appropriate program for any one student needs to be worked out with his or her Advisor. Some fields, for example, are more structured, and a sequence of courses can be defined. Other fields are inherently less structured, and the student should be encouraged to draw on a wide range of faculty and campus resources within and outside of the Construction Management program. However, in the interests of equity and clarity, this paper presents the general outline of a likely program that would challenge a student and result in reasonable progress toward the Ph.D. degree. Each student should actively work with his or her Advisor to develop the set of courses that should prepare him or her in both the broad area of Construction Management and their proposed Major and Minor specialties. Each student is strongly advised to consult with his or her Advisor as early as possible to start the process of planning his or her customized course curriculum.

In order to gain a broad foundation in Construction Management as well as detailed background knowledge sufficient to prepare the student to do research and master the competencies described above, each new student should:

- Enroll in required core Construction Management courses;
- Take the one of the continuing research seminars in the School closest to their research interests; and,
- Work with their Advisor to identify and take a set of advanced courses tailored to their interests from the Construction Management program and other departments on campus.

To gain a broad foundation in Construction Management, students who do not already have a Construction Management master's degree should take the core Construction Management courses. Ph.D. students are expected in their first semester/quarter to enroll in a continuing research seminar in the School closest to their research interests, and attend one of the continuing research seminars each semester/quarter. This requirement may be fulfilled by a research seminar in another department, with the approval of the student's Advisor, but students are still expected to actively participate in the intellectual activities of the Construction Management Program.

Mastery of three subject areas is required for the Preliminary Exam. The preparation is usually done by means of coursework in three areas, one Major and two Minor subject areas that draw upon, or is embedded within, many other disciplines and professions. Depending upon the student's focus, the process of specialization should normally require a mastery of at least one affiliated discipline. This subject area should develop the foundation for a possible dissertation research topic.

The Major subject area requires a coherent program of at least 12 semester/18 quarter units of graduate courses or the equivalent, with a GPA of 3.5 or better (Most students should take considerably more than 12 units in the Major area).

Each Minor subject area is usually composed of at least 6 semester/9 quarter units. Each Minor subject area must have an orientation different from the Major program, and the courses in the Minor must primarily contain material that does not overlap with the Major program. The student should maintain a minimum GPA of 3.0 in Minor fields, and only courses completed with a grade of B or above can count towards the course requirement.

Certification of the Competency Requirement

Usually students should acquire the competencies through coursework. Each student should confer with his or her Advisor about how to demonstrate mastery. The student's Advisor should certify that he or she has gained the core set of skills discussed above. However, if the Advisor is uncertain about the student's skills in any of these areas, it has the option to impose additional requirements or exams. Students may request a review of such decisions by the Head Graduate Program Coordinator or Department Chair.

Written Summary Report and Synthesis of Coursework

As part of the transition from coursework to the Dissertation, each student should prepare a written summary and synthesis of his or her work up to this point. The purpose of this is to give the Advisor an overview of the student's work, and to allow the student to reflect upon and synthesize his or her work up to this point. This is neither a Dissertation Proposal (see below) nor a comprehensive review of the literature (although it should contain references to the literature).

Upper division undergraduate courses may not count towards the Minor unit requirement, although they may be required as prerequisites. It is, rather, the student's analytical and synthetic reflections on how his or her work ties together, the nature and shape of the Major and Minor fields, how the fields fit together, and the important research issues. It should not duplicate the Dissertation Proposal, though it may serve as a prolegomenon to it. The Advisor may wave this requirement if it is satisfied that coursework has been well structured and the student's understanding of the field is well integrated.

This requirement reflects that students have the option to take a highly structured sequence of coursework that is designed to be cumulative, or to invent an interdisciplinary field consisting of courses without a cumulative content.

The Preliminary Exam

The intent of the Preliminary Exam is to ascertain the breadth of a student's knowledge and preparation. Three fields are considered necessary for that breadth. The student should be able to exhibit knowledge and understanding of the fundamental facts and principles inherent in his or her fields of study. The exam also enables the faculty to assess students' preparedness for a research career. The faculty examiners should look for evidence that students have the ability to think incisively and critically about both the theoretical and practical aspects of the field. In Construction Management, students are expected to present the topic for the Dissertation as part of the Preliminary Exam and answer questions about how they should pursue the research necessary to develop the selected topic.

A typical Preliminary Exam lasts approximately three hours. Usually, the student takes the Preliminary Exam within one semester/quarter of having completed the requirements. If the student does not pass, the exam may be retaken one time. A student must be registered to take the Preliminary Examination.

The Preliminary Exam Committee

The Preliminary Exam Committee consists of four faculty members. At least two must be from the Construction Management program; at least one must be from another department, and up to two may be from another department. The chair and the designated outside member must be members of the Graduate Faculty.

The Dissertation Proposal

As part of the Preliminary Exam, the student prepares a Dissertation Proposal describing a plan for research that should be a significant original research contribution to the field of Construction Management. The written Dissertation Proposal normally includes:

- A concise problem statement that summarizes the central thesis.
- A motivation for the problem.
- A description of previous research in the area.
- A description of the relevance of preparatory coursework in the area.
- A summary of the course work done towards the Dissertation.
- A statement of how the student should attempt to investigate or support the thesis.
- A timetable for the student's Dissertation work, and (normally) a list of deliverables.

Summary of the Preliminary Exam Requirements

1. Meet the Graduate Division's eligibility requirements
2. Meet the Construction Management eligibility requirements
3. Form a Preliminary Exam Committee
4. Complete Dissertation Proposal
5. Pass the Preliminary Exam
6. The university regulations concerning the oral Preliminary Exam can be found in the *Graduate Advisor's Handbook*.

The Dissertation Committee

Shortly after passing the Preliminary Exam, the student forms a Dissertation Committee. The student's Ph.D. Advisor usually chairs the Committee. The Dissertation Committee will evaluate the Dissertation Proposal, and review and approve the final Dissertation. The Committee must include at least two regular Construction Management faculty members and one Graduate Faculty member from another department on campus.

The Dissertation Proposal

After passing the Preliminary Exam, the student completes (with any needed revisions) the Dissertation Proposal. After the Dissertation Committee approves the proposal, and no later than the end of the semester/quarter following the one in which the Dissertation Proposal is approved, the student files an Application for Advancement to Candidacy. In approving this Application, the Head Graduate Advisor approves the Dissertation Committee as well.

Residency

Students must have been in academic residence for at least four semester/six quarters to qualify for a Ph.D. In order for a semester/quarter to count as academic residence, a student must enroll for at least four semester/six quarter units of graduate-level courses (These 4/6 units do not necessarily satisfy the requirements for full-time study.).

The graduate division requires that students be registered during the semester/quarter in which the preliminary exam is taken. Construction Management also requires that students be registered in the semester/quarter in which the dissertation is approved in order to present his or her findings to the scholarly community. This second semester/quarter requirement may be waived if the student presents good reasons why residence would be difficult, with the concurrence of the student's Advisor and the Head Graduate Advisor.

The Ph.D. Advisor must be a member of the Graduate Faculty. The chair may be a faculty member outside of Construction Management, upon the approval of the Dean of the Graduate Division, but in such cases, a regular Construction Management faculty member should serve as a co-Advisor.

If the student’s Advisor leaves the university after the student has begun the Dissertation requirements, the student should consult with the Ph.D. Committee as to what course of action to follow. In some cases, the student and the Committee may decide to pick a new Advisor; in other cases, the student and the Committee may decide to keep the student’s original Advisor while choosing a regular Construction Management faculty member to co-advise.

The Ph.D. Dissertation

After receiving approval of the Dissertation Proposal, the student continues the Dissertation research and writing. During this period, the student should meet regularly with his or her Dissertation Chair and report regularly to the Dissertation Committee. Each semester/quarter, the student prepares a summary of progress, supported by copies of any writing that he or she may have done.

In accord with the standards of his or her specialization, the student is expected to publish the Dissertation and Major results of the Dissertation research. The Ph.D. Dissertation represents the cumulative accomplishment of the Ph.D. process. The Ph.D. Dissertation must be an original and significant contribution to research. Results from Ph.D. Dissertations are published (except in extremely rare or exceptional circumstances).

To share new knowledge with colleagues and prepare for job interviews, Ph.D. students present the principal results of their Dissertation research and take questions and challenges from the community on the Dissertation work. The Dissertation Committee and other faculty members and students from the university community, both inside and outside Construction Management usually attend. This presentation informs the university community about the research that takes place in the Construction Management program and provides the student with valuable preparation for other research presentations (including job interviews). This presentation generally takes place in the last semester/quarter in residence or in the semester/quarter in which the Dissertation is filed. It should be scheduled so that as many interested people as possible can attend.

When the Dissertation is completed, it must be approved and signed by all the members of the Ph.D. Committee. Upon successful completion of the Dissertation and all prior requirements, the student should be awarded the Ph.D.

Summary of Requirements

Most students should complete the course requirements in about two years. After completing these requirements, a student who does not already possess a Construction Management degree may petition for a master's degree, and for permission to take the oral Preliminary Exam. The Construction Management degree requires that the student complete: (a) a program of 28 semester/42 quarter units of course credit, approved by the faculty, with an average grade of B or higher; and (b) a Thesis/Project approved under conditions designated by the faculty. However, because the program may be highly customized for each student, it is not possible to define a blanket timetable requirement other than the normative guideline described above. Thus, the student's Advisor should decide whether he or she is making adequate progress towards the degree, and communicate specific requirements and recommendations in writing each semester/quarter.

If the student has demonstrated sufficient mastery of the field, the student's faculty Advisor (in consultation with all interested faculties) should grant permission for the student to proceed to the oral Preliminary Exam. If the student has not demonstrated sufficient mastery of the field, the Committee may award the student a Construction Management degree, but not grant permission to take the oral Preliminary Exam or to complete the Ph.D. program.

Summary of the procedure for meeting the requirements once the coursework requirements have been fulfilled are:

1. Form the Dissertation Committee.
2. Complete the Dissertation Proposal.
3. Defend the Dissertation Proposal in an Oral Examination.

4. Have Dissertation Proposal approved by Dissertation Committee.
5. Complete and have the application for advancement to candidacy approved.
6. Meet the residency requirement.
7. Complete the Dissertation.
8. When required, make in public an oral defense of the Dissertation results.
9. Receive sign-off by all Dissertation Committee members.

The Ph.D. Dissertation represents the cumulative accomplishment of the Ph.D. process. The Ph.D. Dissertation must be an original and significant contribution to research. A Ph.D. program in Construction Management requires a mastery of academics and practice in the broad area of Management and Science. It involves in-depth knowledge of specific areas of construction that involve skills in problem solving and the analysis of information; and the capacity to make original contributions to the field.

What has been outlined in this paper corresponds to a layered model of graduate studies where students begin by developing a broad base of knowledge, and, building on that, progressively deeper understanding and skill in fields of increasing specialization. While a Ph.D. in Construction Management offers a structured curriculum to develop research capabilities and skills, the program is also flexible, in recognition that each individual student's program should be unique.

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Simulation Gaming in Construction: ER, The *E*quipment *R*eplacement Game

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Simulation gaming has been used to add an exciting feature to classroom instructions in a variety of disciplines. Generally, simulation games mimic real life situations in order to develop a wide array of professional skills. This paper firstly surveys simulation games used in the construction management domain including, estimating, bidding, and negotiation. A brief description of the surveyed games and the learning objectives are provided. Secondly, the paper describes the EQUIPMENT REPLACEMENT (ER) game. ER is a multi-player game that can be used in teaching and explaining the different effects of various equipment buy/sell strategies on the economic performance of construction companies. The game is aimed at simulating the buy and sells decisions of construction equipment and can be used to simulate various strategies for equipment with different cost magnitudes. The probabilistic aspect of demand in the construction market is incorporated and the pedagogical aspects of the ER game are also discussed. The game is implemented as an Excel add-in using Visual Basic for Applications (VBA).

Key Words: Construction Equipment, Game, Cost Models, Simulation, Replacement Analysis, Construction Management

Introduction

Simulation games are an excellent way to provide practical decision-making and management experiences. Their teaching effectiveness is usually very high as they provide a unique way to reinforce the theory discussed in the classroom environment (Frazer, 1975). As the players generally become deeply involved in the gaming situation, they develop a desire in doing well in the game and therefore the simulation becomes closer to reality. These games provide a chance to experiment with, or test, ideas and theories acquired elsewhere. Obviously simulation gaming is not a substitute for more formal approaches to teaching the theories and methods of the particular topics, however, it complements these approaches. Integrating the standard formal teaching methods and simulation games as a laboratory to test and reinforce the relevance of theories, can be a very effective teaching method. In this paper, we discuss simulation games in general and survey the construction-specific simulation games. Next, we focus specifically on the Equipment Replacement (ER) game, which emphasizes the replacement decisions of construction equipment. Finally, we present the computer implementation and go through a brief sample run of the game.

Simulation Game in Construction

In the construction domain a number of simulation games have been proposed. These games demonstrate a multitude of concepts important to the construction professional ranging from bidding practices to negotiation.

Construction Management Game

The Construction Management Game is one of the earliest games developed in the construction domain by Au, et al (1969). The Construction Management game is an example of simulating the bidding process in the construction industry. Teams of players are cast in the roles of managers in construction companies. Each company is a general contractor that subcontracts and coordinates all portions of a building construction project either to individual subcontractors or to its own operational divisions when awarded a general contract. The goal is to maximize the company's net worth. The teams' performances are calculated in an income statement such as that shown in Table 1.

Table 1

Evaluating A Company's Performance In A Construction Management Game (Au, et al 1969)

	Income statement	
A.	Income from construction contract	$412,510.00
	Cost of contracts	
B.	Subcontracts and supervision of subcontractors	347,891.00
C.	Field overhead	2,063.00
D.	Gross profit	$62,556.00
	Administrative and general expenses	
E.	Office operating cost	10,921.00
F.	Information costs	650.00
G.	Bidding costs	1,733.00
H.	Interest on existing loans	900.00
I.	Earning before federal learning taxes	$48,352.00
J.	Federal income taxes	17,411.00
K.	Net earnings	30,941.00
L.	Retained earnings at beginning of period	208,422.00
M.	Liquid assets	$239,363.00
	Loans	
N.	Existing loans	60,000.00
O.	New loans (one year notes)	25,000.00
P.	Loans due this time period	10,000.00
Q.	Total cash-on-hand	314,363.00
R.	Retained earnings at end of period	$239,363.00
S.	Percentage gain or loss up to end of period	+19.7%

CONSTRUCTO

The CONSTRUCTO project management game was developed at the University of Illinois by Halpin to integrate the effects of weather and labor productivity into the management of projects in a network format (Halpin, 1973). A simulation approach was adopted using the CYCLONE simulation language to build a real life construction project situation including some of the environmental and economic parameters facing managers. The players are presented with a construction project. In turn, the players are asked to input the activities and crews required among other variables.

SuperBid

SuperBid is a computer simulation model developed in the University of Alberta, that can be used to improve the bidding skills of construction managers (AbouRizk 1992). The SuperBid game is similar to CONSTRUCTO and the project management games, in that a bidding situation is created automatically by the computer using stochastic techniques. However, SuperBid is geared specifically at introducing the concepts of the bidding in the construction management domain using a game format. The players try to increase the profitability of their companies by mainly optimizing their bidding decisions. Similar to the Project Management and CONSTRUCTO games, SuperBid is implemented as a computer program.

Negotiation Game

Another construction related game is the Negotiation Game (Dubziak 1988). The construction Negotiation Game simulates a contract negotiation between a utility and a design/build firm. The negotiation involves only two parties but implies there are several issues to be resolved. Players in the game are assigned to represent one of the two parties and to negotiate the various issues, which include duration, penalties, bonuses, frequency of reports, contract types, percentage profits and legislation. A final contract generally requires an agreement on each of these issues, presented on a form signed by both parties (Table 2).

Table 2

A Negotiated Contract Between CMG Gas And Pipeline Constructors, Inc (Dubziak 1988)

Duration	38 weeks
Penalty for late completion	$6,800 per day
Bonus for early completion	$0 per day
Report format	Traditional CMG form
Frequency of progress report	Weekly
Conform to pending pipeline marking legislation	Yes
Contract type	Fixed fee
Amount of fixed fee	$5,050,000.
Percentage of profit	Not applicable
CMG Gas clerk on site	Yes
Penalty for late starting date	$3,000 per day
Signed:	
CMG Gas representative	
Pipeline Constructors, Inc.	

Parade of Trade Game

The main learning objective of the parade of trade game by Choo et al (1999) is to explain the impact of workflow variability on succeeding trade performance. The game demonstrates to the players how small changes in the variability of tasks and dependence can influence the construction environment. In the game, multiple trades follow each other in a linear sequence and work output by one trade is handed off to the next trade. This can be simulated using dice or using a developed computer program.

Lego Bridge Game

Beliveau (1991a) has developed an interesting construction simulation game using Legos. The game presents the players with a multitude of real life issues in a simplified way. The game involves building one of two bridges using Legos. The players have to decide which bridge to build, prepare an estimate for the bridge (in terms of how many Lego) pieces and finally build the bridge. The teams are rewarded for lower cost due to short building time and are penalized for over or underestimating. As can be seen there are a number of simulation games developed for the construction industry.

Road Building Negotiation Game

The road-building-negotiation game is a group negotiation game that can effectively demonstrate the impact of a well-developed strategy in negotiations (Beliveau, 1991b). In the game, two teams of negotiators are given the objective to build the longest continuous road that passes through a number of plots of land. The plots are assigned equally between the players but the players can trade the plots between them to increase their road's length. The teams are given a few minutes before negotiation to come up with a defined strategy for negotiation. Further, the negotiation time is limited. The team with the longest continuous road is declared the winner. Often two teams do not reach an agreement in the allocated time and both fail to build any roads at all. The moral of the game is to try to negotiate a win-win situation in order to reach beneficial agreements in the allocated time.

The Marketing Game

The Marketing game is developed at Bradley University (Bichot, 2001) and is aimed at enhancing the awareness of construction managers about the importance of marketing in the construction industry. The various marketing techniques that can be used in the construction industry are first presented to the players. Then the players are asked to develop and perform a simulated marketing plan over a number of simulated years (periods) and the players are assessed based on the effectiveness of their marketing strategies and techniques. A comparison of the games described above is seen in Table 3.

Table 3

A Comparison Chart of the Simulation Games Available for the Construction Management Field

	Game	Focus Area	Time Frame Required	Computer Implementation Needed	Limit on Number of Players/Teams	Main Construction Courses Where Applicable
1	***Construction Management Game***	*General Management skills*	*1.5hr to 1 semester*	*YES*	*Optimum 4-6 teams*	*Construction Management*
2	***Negotiation Game***	*Tradeoffs and Negotiation skill*	*1.5hr*	*NO*	*NO*	*Contract Management and Administration Courses*
3	***Parade of Trade Game***	*Effect of variability on construction productivity*	*1hr*	*YES*	*NO*	*Construction Productivity Improvement*
4	***CONSTRUCTO***	*General Management skills*	*NA*	*YES*	*NA*	*Construction Management*
5	***Super-Bid***	*Bidding skills*	*1hr*	*YES*	*NO*	*Estimating and Construction Management*
6	***Lego Game***	*Estimating and Construction Planning*	*1.5hr*	*NO*	*Optimum 4-6 teams*	*Scheduling, Company Management*
7	***Road Building Negotiation Game***	*Group Negotiation and planning*	*1hr*	*NO*	*Optimum 4-6 teams*	*Construction Management*
8	***Equipment Replacement Game***	*Equipment and resource management with market demand*	*1.5hr to 1 semester*	*Yes*	*Optimum 4 teams*	*Construction and Company Management*
9	***The Marketing Game***	*Construction Marketing, Company management.*	*1hr*	*Yes*	*4*	*Introduction to construction, Marketing Courses*

Description of the Equipment Replacement Problem

Equipment management is becoming a major role in the everyday practice for construction professionals. Equipment costs are a major cost item in projects and the correct management of the construction equipment is a significant factor in the success of any construction company. The longer a piece of construction equipment stays in service the higher will be its maintenance cost and the lower the productivity. When a machine reaches a certain age, it may be more economical to replace it. The equipment replacement problem thus is to determine the most economical age of a machine. Generally, we study the replacement policy over n years. At the start of each year, we decide whether to keep the machine in service for 1 more year, or sell and buy new machines. Let $r(t)$ and $c(t)$ represent the yearly revenue and the total operating cost of a t-year-old machine. Also, let $s(t)$ be the salvage value of the machines that have been in service for t years. The total cost of acquiring new machines at year t is $I(t)$.

Therefore the goal is to find the decisions that maximize *f(t)*,

$$f(t) = r(t) + s(t) - I(t) - c(t) + f(t-1)$$

We limit the number of machines that can be bought each period to *k* and the periods are limited to *n* periods. The winner therefore is the team with the highest *f(n).* At the end of the game, each team will have a matrix whose elements represent the equipment purchasing decisions for each machine for each quarter. For example for team b,

$$D_b = \begin{vmatrix} x_{11} & x_{12} & x_{1j} & .. & x_{1k} \\ x_{21} & x_{22} & x_{tj} & .. & .. \\ .. & .. & .. & & x_{nk} \end{vmatrix}$$

Such that for period *t*

$$x_{tj} = \begin{cases} 0 & \text{if no machine is purchased} \\ 1 & \text{if machine A} \\ 2 & \text{if machine B} \\ 3 & \text{if machine C} \end{cases}$$

Each team will also have *n* vectors representing the selling decisions for each quarter,

$$S_{bt} = \begin{vmatrix} y_{t,1} & y_{t,2} & y_{t,i} & .. & y_{t,t*k} \end{vmatrix}$$

$$\text{Such that for } \forall t,\ y_i = \begin{cases} 0 & \text{if no sell} \\ 1 & \text{if sell} \end{cases}$$

$$\text{Subject to } \forall i,\ \sum_{t=0}^{n} y_{t,i} = (0,1)$$

The elements of this matrix and vectors are the decision variables. Here we define that the market demand *d(t)* is stochastic. Although, forecasting the market demand in real life is a complex problem we simplify the problem by assuming that the demand follows a beta distribution such that the probability at time t of a market demand *d(t)* is,

$$P[d(t)] = \left\{ \frac{(\alpha+\beta-1)!}{(\alpha-1)!(\beta-1)!} \left(\frac{d(t)}{w}\right)^{\alpha-1} \left(1 - \frac{d(t)}{w}\right)^{\beta-1} \text{if } 0 < x < w \right.$$

where *w* is set to equal the maximum demand and is equal to $d_{(t-1)}+I$, where I is the expected increase in demand and $d_{(t=0)} = I_o$. The shape parameters α and β are used to control the demand profile, either to increase or reduce the expected demand.

Although any model can be used for market demand, this model provides for the necessary variability for the simulation game, such that the revenue for each team is not fixed. The revenue is determined from one period to the other by the teams' production capacity and the market demand by the following formula,

$$r(t) = \begin{cases} p(t) * P & \text{when } d(t) > p(t) \\ d(t) * P & \text{when } p(t) < d(t) \end{cases}$$

And, $p(t)=N_1 \times P_1 + N_2 X P_2 + N_3 \times P_3$, where N_1, N_2, N_3 are the number of machines types 1,2,3 respectively and P_1, P_2, P_3 are the production capacities of machines types 1,2,3 respectively, where $p(t)$ and $d(t)$ is the production capacity and the demand at time t and P is the price per unit. When the demand is less than the production capacity the program selects the machines with the lower variable cost to do the work. This might not be the best alternative, but this is set as a rule of the game and is made known to all teams. This is an example of striping the real life situation, discussed earlier, to concentrate more on the equipment buy/sell decisions. Although the exact mathematical optimum solution to this problem is not considered here, it would be useful to understand how a solution to this problem can be obtained. The equipment replacement problem has been traditionally formulated as a dynamic programming (DP) problem and solved using standard DP techniques. However, because we are considering different machines types and the different buy/sell strategies and not just replacement, the problem has been formulated above an integer-programming problem. These kinds of problems are usually solved using techniques like branch and bound. The added complexity here is the stochastic demand and that fact that the objective function is discontinuous. Therefore, to find a solution (or optimum strategy) to this problem we have to resort to simulation techniques and optimization methods that are suitable for discontinuous problems like genetic algorithms. Even then, using these techniques a global optimum solution is not guaranteed. The next section describes the simulation game version of this problem.

Description of the ER game

EQUIPMENT REPLACEMENT game is optimally played with four teams, although other team sizes are possible. Each team is responsible for managing the excavator fleet of an excavating contractor. The game is played in 12 simulated quarters. At each quarter, the teams can decide to buy new excavators or sell existing ones depending on the efficiency of the machines and the expected production demand in the future. The production units are considered to be cubic yards of work. The price per cubic yard is fixed at $50 and the market demand or number of jobs is independent of the decisions made by the teams.

Three types of machines are available to satisfy the demand. Suggested data for each type of machine is shown in table 1.

Rules of the Game

- In the game, we will assume that any advancement in the technology and the quality of the excavators is equated by inflation. This means that all new machines will always have the same initial cost and variable costs in spite of when they were purchased. However there is an increase in the variable cost per quarter due to inflation and decreased efficiency. Machines A are less automated than Machines B and Machines C are less automated than machine B and therefore the variable costs with Machines A increase at a faster rate. Salvage value at retirement is calculated using the double declining balance. Other depreciating methods can be also be used by making minor modification to the game. The double declining balance depreciation was used to emphasize the effect of depreciation on the decisions made.

- The number of jobs available is approximated by the demand per quarter in terms of cubic yards/ quarter. The demand begins at 20,000cubic yards/year for each team and increases each year. The size of each year's increase is randomly generated between 0 and 40,000 cubic yard according to a beta distribution as described above. This range allows the moderator to change the variability of the market demand. If a team does not have enough machines to satisfy the demand, then their sales will be determined by the capacity of the machines they have. If a team has excess capacity, then the full demand will be satisfied by using machines in the order of their variable costs with the machine having the lowest variable cost per unit being used first.

- Teams cannot change buy or sell decisions after they are made, and the teams are also not allowed to make future buy or sell decisions.

- A company can only buy a maximum of 5 machines of each type, in each quarter. Each team begins with $200,000 in cash. Machines can be bought on margin with an interest rate of 15%.

- For the purpose of the game, retiring a machine is considered a tax benefit. Machines will be identified for each team sequentially in the order in which they were purchased.

- Cash balances earn an interest of 12%. The cash position of each team is evaluated after all costs are paid and before the income is received. (Negative cash balances incur a 15% charge.) Taxes on profits are calculated at 10%.

- Teams will make decisions for 10 quarters but the game will last for 12. At the end of the 12^{th} quarter, the team with the highest book value is the winner.

All the variables discussed above can be changed to explore different effects and scenarios. Modifying all these variables is made possible in the computer implementation described below.

Computer Implementation

The game was implemented as an add-in to Excel in Visual Basic for Applications. Implementing the game as an Excel add-in is beneficial because most students are already familiar with the interface and also because that allows the student to build their own spreadsheet models, during the simulation game, for verification and analysis of their decisions. Visual Basic was used to program the macros responsible for the different calculations and for administering the game. The application consists of four identical workbooks (one for each team) and a separate workbook for the moderator. The moderator workbook is where the global variables of the simulation game can be changed, such as the initial cash for each team, the prices of the machines the depreciation method used or the life and variable costs of the machines. The player's workbooks are where each team enters the decisions for each quarter.

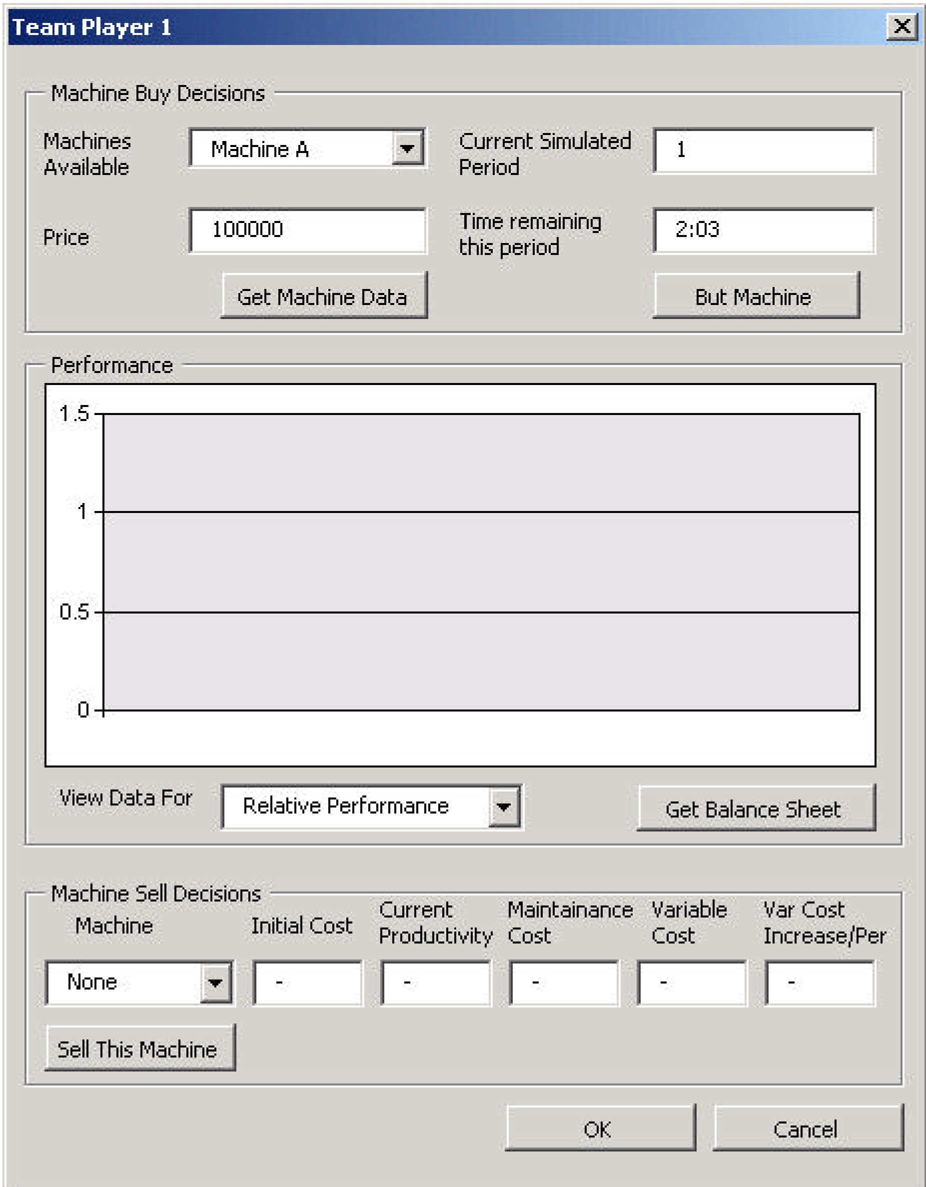

Figure 1: The Players Interface

Furthermore, the players' workbook is where each team can track its financial statement and its current position. The formulae are all predefined and protected, so although each team can see how it is doing they cannot change the rules of the game. Each team enters the number of each machine kind to buy for each quarter and this is added to their database of machines, which can be view on a separate sheet. Each team can select a specific machine at any time and hit the sell button to sell the machine. This updates their financial position automatically. Also each team can select any machine they own from the database and get a complete report on that particular machine including its book value its current production, its current variable cost etc.

The players also get a chart showing how the different attributes of the game are progressing with time like their cash and income. The different teams also get an index chart showing their current positions with respect to each of the other teams. The workbooks for the various teams are linked to the moderator workbook who in turn sets the future demand. The moderator can also reset the game and set the simulated time for each quarter as can be seen in figure 2. Although generally not recommended, the moderator can adjust the program so that certain teams get either an advantage or a handicap by changing variables like their initial cash. At the end of the game, charts are generated to show what decisions each team made and how that affected their position. These can be used in post-game discussions.

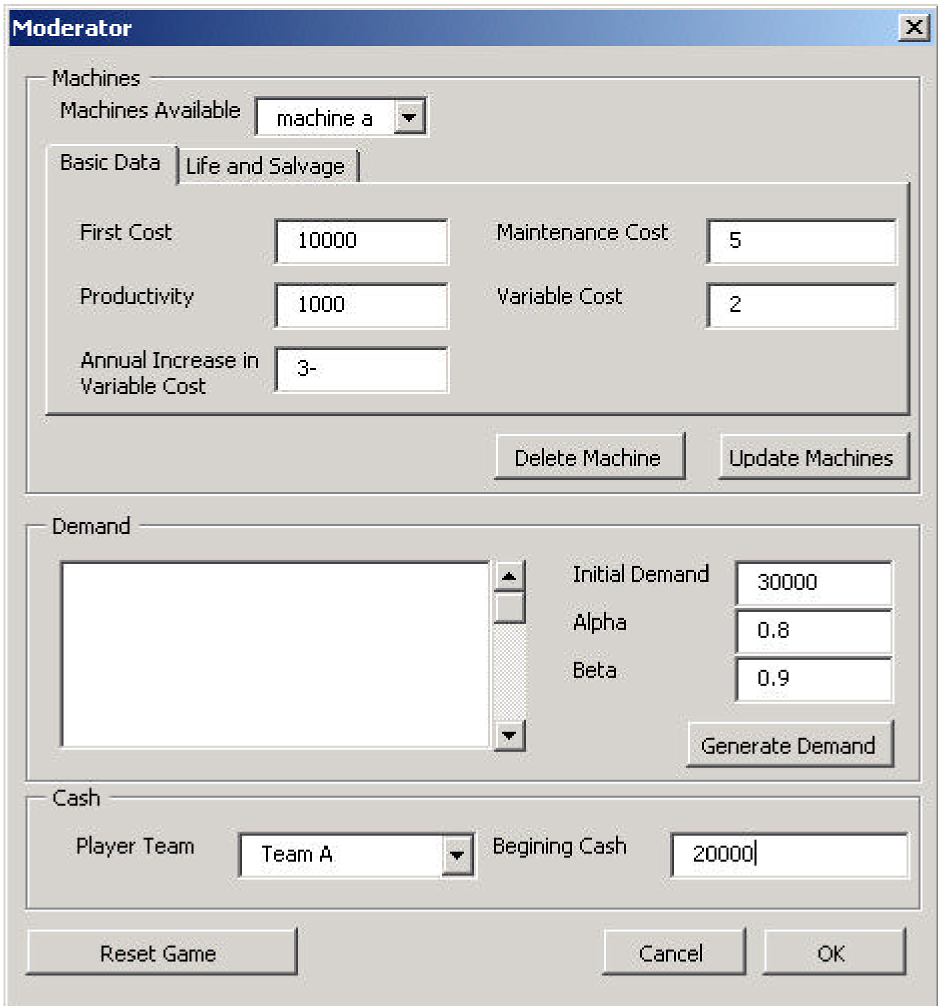

Figure 1: The Moderator Interface

A Sample Run

In this section, we will describe a typical run of the replacement game. The game here was played with four groups of students. The groups had members ranging from 2 to 4 students each. The game took about one whole class session of about an hour and twenty minutes. Alternatively, this game can be played over extended period. In this case, students can conduct more detailed risk analysis of market demand (i.e. Monte Carlo Simulations) using add-ins to excel like @Risk or Crystal Ball. That included the time for discussion of the results and the various strategies. An effective method to make these games more realistic is to add some sort of added incentive for the winner. This can range from small percentage grade points to simple prizes such as books or even a symbolic amount of waged money! A 1% grade point was offered to the winning team members.

The production demand is seen in figure 3. The actual demand for each simulation quarter was generated using the beta distribution as described above and was revealed at the beginning of each quarter. This added the challenge for the different teams to try to predict the future demand and but the increase trend was disclosed to all teams to take out the task of forecasting whether or not a particular demand trend will continue. A limitation here is the number of quarters of the simulation was limited to 12 quarters, which meant that also the number of demand trends was limited.

Table 4

The Position of Team A after two quarters

REVENUE from selling machines	$68,326.25
REVENUE from production	80,000
Total Expenditures	3,300
NET INCOME	125,026
INTEREST	9,754
TAXES	64890.094
TOTAL	69,890
BOOK VALUE ON MACHINES	160,000
CURRENT BOOK VALUE	229,89

Table 5

Data for the sample run

Machines A	***Machines B***	***Machines C***
Initial Cost of Machines	Initial Cost of Machines	Initial Cost of Machines
$100,000	$220,000	$250,000
Production Capacity	Production Capacity	Production Capacity
5000 cubic yards/quarter	6000 cubic yards/quarter	7000/quarter
Maintenance Cost	Maintenance Cost	Maintenance Cost
$8000/year	$8000/year	$8000/year
Variable Cost (first year)	Variable Cost (first year)	Variable Cost (first year)
$7/ cubic yard with a $7/year	$8/ cubic yard with a $3/year	$7/ cubic yard with a $7/year

It is important to note that different predefined demand curves can be experimented with resulting obviously in different strategies. In addition, the demand trend can be shown at the start of the simulation to allow the teams to formulate a strategy accordingly. Alternatively, a projected and an actual demand curves can be used with the projected demand curve being shown before the simulation and the actual demand being shown at the beginning of every quarter only.

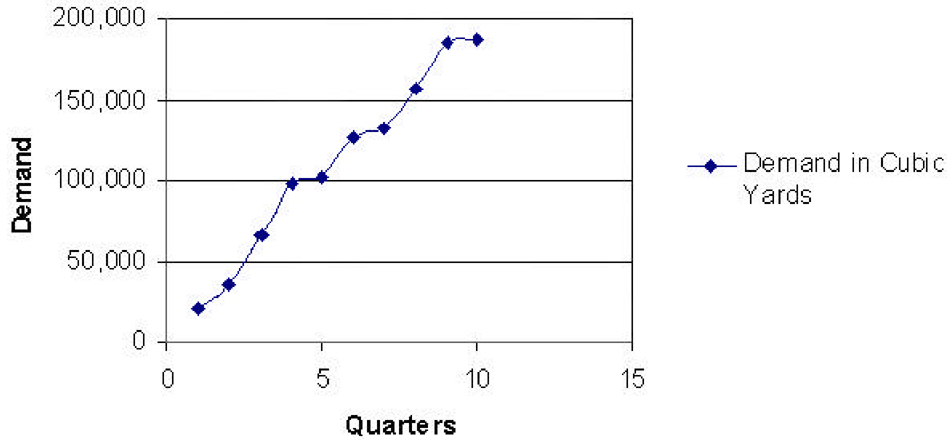

Figure 3: The Production Demand

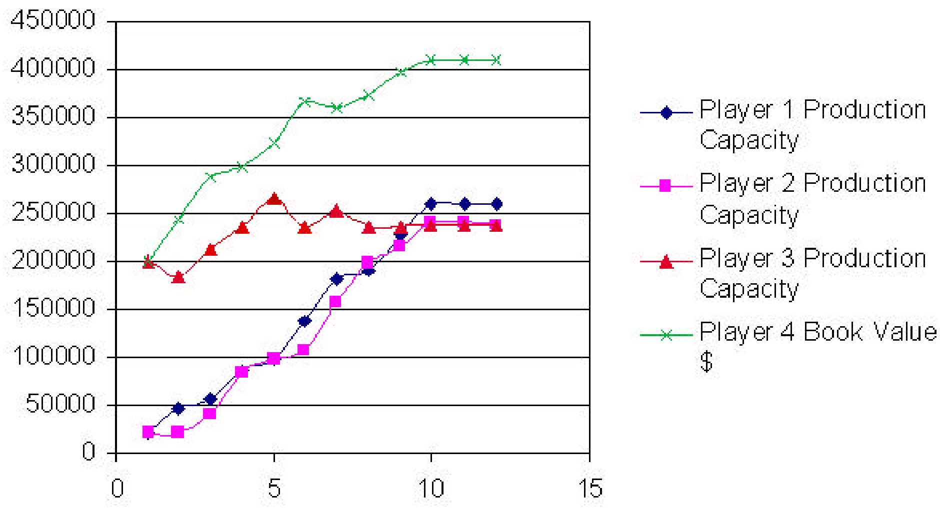

Figure 4: The Production Capacity of the Four Teams

The data used for this simulation game is shown in table 5. This data can be easily changed to reflect different situations. Changing this data will have an effect on the number of expected buy and sell decisions to be made by each team. For example, by increasing the production capacity of the machines while keeping the demand constant, the number of buy sell decisions will decrease as single purchases will be able to cover more production demand.

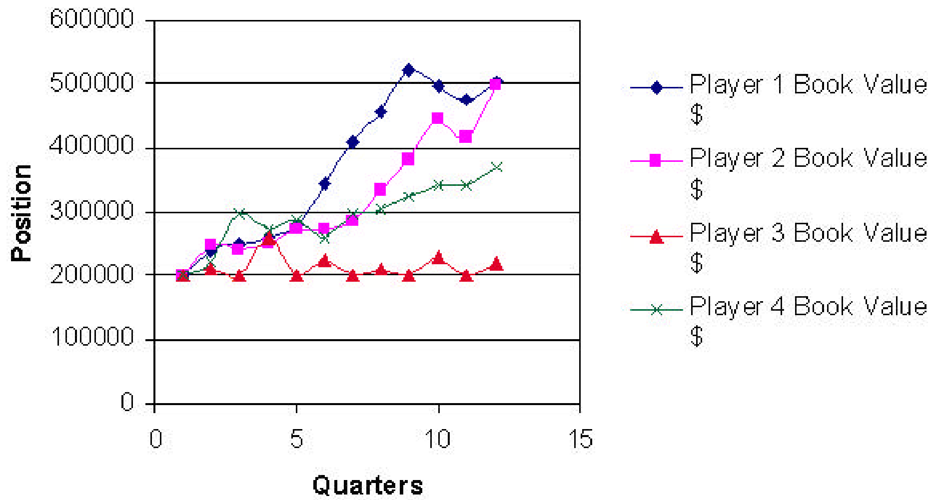

Figure 5: The Performance of the Four Teams

The production capacity (in cubic yards) of the four teams is shown in figure 4, and their financial position (net worth in $) is shown in figure 5. Although several factors will affect who wins the game, the correct production capacity is a critical factor. As can be seen form the charts, the simulation ended with teams one and two almost in a tie. Team 4 had over estimated the market demand and even though a sell decision was made at the end of the game (as can be seen from the flat potion at periods 11 to 15), the team ended with an excess of production capacity to which maintenance and variable costs had to be charged. The performance of team 3 on the other hand was shadowed by the abrupt and jerky buy/sell decisions.

Teams one and two mimicked the demand curve and tried to follow the trend in a tit-for-tat strategy. Quick responses to the market changes and following the expected market demand change are some of the important lessons learned. Group decision-making within the various teams is another. Teams were encouraged to build their own spreadsheets to verify the calculations. As the teams participating in this game indicated, managing the company's inventory of machines and how much cost is incurred was an important issue. . Team one calculated the ratio of their inventory costs (variable cost + maintenance) to their revenues as a measure to manage their inventory.

The overall combined performance of the teams and their strategies were recorded for future discussions and study. After the simulation was run some questions where set forward for discussion like,

- Did you plan for a strategy before the game? What was your strategy?
- How did you project the demand for the next quarter?
- Who keyed in the decisions in the computer?

In addition, a student survey was conducted at the end of the session to try and evaluate the teaching effectiveness of the game and the results are shown in Figure 6. Although, most students agreed that the quality and teaching effectiveness of the game was superior, the lowest score was given to the reality of the game. This may be an indication that we can add more complexity to the game without sacrificing the teaching effectiveness. Also, the program and the interface were seen to be effective.

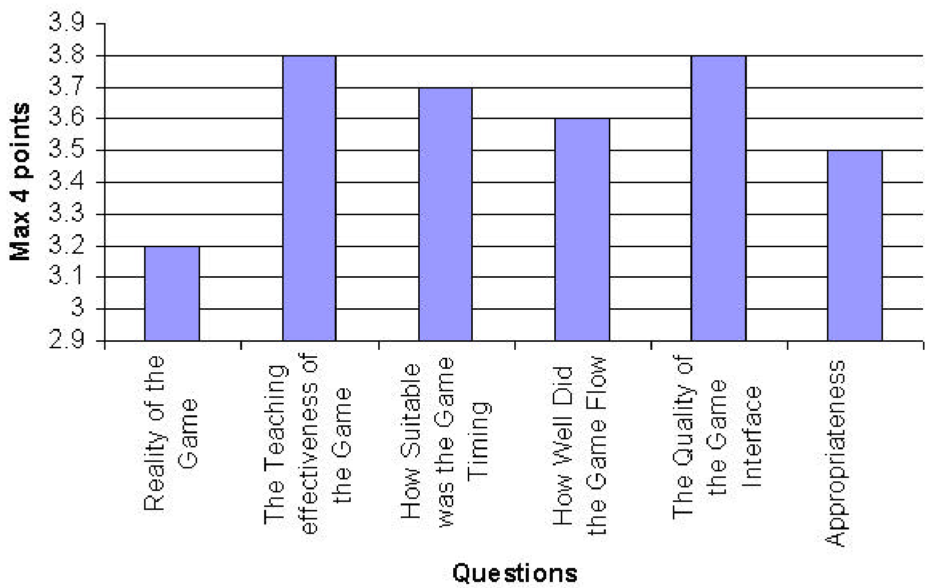

Figure 6: Results of the student survey

Conclusion and Future Research

This paper presented the construction EQUIPEMNT REPLACEMENT game, which was developed as a tool for learning about the effect of buy/sell decisions on the financial performance of a construction company. A formulation of the equipment replacement problem was presented along with the computer implementation of the game. The lessons that can be learned about how the students operate in a team and particularly the interaction of opinions is a valuable element of this simulation game. In addition to the educational features of the game, probably the most important lesson that is learned is the leadership role and that the usually effective leaders are vigilant to make sure that the ideas of all players are considered and that a winning strategy is usually one that the whole team is behind.

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Analysis of a Type I Differing Condition Claim: An Empirical Study to Determine Which Proof Element is Most Frequently Disputed and Which Party Interest Most Often Prevails

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This research paper statistically examines a Type I differing site condition claim and the concomitant proof elements associated therewith necessary to prevail under such a claim by a general contractor. A sample size of 101 cases were observed using the methodology content analysis and statistically measured by the chi-square statistic and Cramer's V measure of association. The results suggest that the only statistically significant association between a favorable or disfavorable award dependency occurred in the direction of the owner. The data measure suggest that the general contractor fails most often to prevail under the issue of whether same has acted reasonably prudent when interpreting construction contract indicates at the pre-bid phase.

Keywords: Differing Site Condition, Unforeseen Site Condition, Type I Claim.

Introduction

The occurrence of a differing site condition creates an inordinate amount of contractual complexity. As a result, the issue differing site condition is the most frequently litigated construction dispute (Richter & Mitchell, 1982). By definition, a *differing condition* is a physical condition at the construction site that is either: a) not indicated in the contract documents, or b) is in some way different from a work condition normally applicable to the construction project and, thus not known to exist at the time the contractor offers to perform the project scope of work. In short, the bidding documents simply do not accurately represent a pre-existing site condition. Thus, unless the owner has included a clause that provides the contractor with an equitable remedy (time and/or money adjustment), the contractor must absorb the added cost stemming from this unexpected work site condition (Richter & Mitchell, 1982). Should this be the case, then the owner is typically subject to liability for a breach of contract resulting from a cause of action emanating from either: a) misrepresentation; b) superior knowledge regarding project data; or c) implied warranty to accurately represent project data *United States v. Spearin*, 248 U.S. 132, 136, (1918). Furthermore, simply because a project owner incorporates a differing site condition clause to mitigate or preclude a law suit for breach of contract does not automatically necessitate an immediate favorable equitable adjustment to the contract price for the construction contractor. In essence, such a clause does not guarantee an implied right to an equitable contract adjustment resulting from a differing site condition claim. The contractor must still comply with each condition precedent stipulated to by the general and special conditions of the contract to effectuate a successful claim (Cushman, Bigda, & Sadur, 1985). Although there exist a Type I and Type II differing condition claim, this research study examines a Type I condition. To this end, the purpose of this paper is to investigate the legal element(s) that a construction contractor frequently fails to prove when litigating a Type I differing site condition claim that results in a disfavorable court outcome that shifts the risk of a differing site condition provision to the contractor.

Purpose of a Differing Site Condition Clause

Prior to the advent of the differing site condition clause, under common law, a contractor was deemed to have accepted the contractual risk of an unforeseen site condition affecting project scope (Cushman, Bigda, & Sapers, 1985). Thus, the contractor either experienced a financial gain or loss on the contract price as a function of not encountering or encountering the risk of an unforeseen condition at the project site (Nagle, 1992). As a result, a contractor typically includes within the contract price a cost contingency factor allocating cost to the potential probability of encountering a differing condition at the site not represented by the bidding documents. Ostensibly, the inclusion of a contingency factor increases the bid price to the project owner, thereby creating a financial detriment to the project owner and a financial windfall to the contractor should the unforeseen condition not materialize (Riggs, Dorris, Staek, Hafer, Hoy, & Brown, 1998). As a consequence, currently both the public and private owners incorporate a differing condition clause to negate a related differing site condition contingency cost, thereby attempting to allocate unknown contractual risk more equitably amongst the contracting parties (Anderson, 1947). The differing site condition provision therefore serves the purpose of reallocating contractual risk to the owner by requiring the owner to modify the construction contract price and time during contractual performance to account for a changing site circumstance (Code of Federal Regulation, 1996).

Types of Differing Site Conditions

Since 1927, the Federal government has employed the equitable adjustment clause for a change condition. The current version of the Federal Government's differing conditions clause provides at Federal Requisition Regulation 52.236-2 (FAR), April, 1984, two distinct categories that descriptively define an unforeseen site condition that allows a contractor to claim for an equitable adjustment to contract price *Rice v. United*, 317 U.S. 61, (1942). Technically speaking, an unforeseen contract condition is categorically defined as either: a) Type I, or b) Type II site condition (McClure, 1984).

A Type I condition is one that differs from those *indicates* in the contract documents. In order to maintain a Type I differing site condition claim under Federal Acquisition Regulation 52.236-2, the governmental agency boards and United States Court System have held that the construction contractor must satisfy certain specified elements of proof. Each proof element is as follows: a) that the conditions indicated must differ materially from those encountered; b) that the conditions actually encountered must have been reasonably unforeseeable based on all information available to the contract; c) that the contractor must have reasonably relied upon its interpretation of the contract and contract related documents; d) that the contractor must have been damaged as a result of the material; e) subsurface conditions are actually encountered; and (f) the contractor acted as a reasonably prudent contractor when interpreting the contract documents *Stuyvesant Dredging Company v. United States,* 834 F.2d 1576 (Fed. Circ., 1987).

A Type II condition is not addressed or indicated in the contract documents, but differs materially from a condition that would ordinarily be encountered at a geographical area. If the condition is known to the contractor at the time of bidding, or if knowledge is imputed to the contractor, recovery is denied. For this reason, a reasonable site inspection by the construction firm prior to bidding is important. If the site condition would have become apparent or is apparent upon a reasonable site investigation, then a equitable adjustment for differing site conditions is barred. This result is owing to the fact that the owner has made no contractual representation to the contractor regarding the physical characteristics at the project site *Alvin H. Leal v. United States*, 276 F.2d 378 (Ct. Cl. 1960). In order for the contractor to establish a favorable Type II claim for equitable adjustment, the contractor must prove two of the three following elements: (a) the condition was unusual and could not be reasonably anticipated by the contractor from prudent study of the contract bid documents, (b) the conditions encountered at the site is materially different from those ordinarily encountered and generally recognized in similar work, and (c) the physical condition at the site was unknown *Youngdale & Sons Const. Co. v. United States,* 27 Fed. Cl. 516, (1984).

For a Type I claim, the primary or fundamental issue is whether the contractor encountered physical site conditions that where materially different from those conditions indicated in the construction contract documents *Pacific Alaska Contractors, Inc. v. United States,* 436 F.2d 461 (Ct. Cl. 1971). Antithetically, by comparison, a Type II claim refers to a physical site condition that is "unknown and unusual" in the sense that same would not normally be expected in a site condition similar in nature to the work encountered and/or required by the construction contract. In essence, a Type II claim does not require analysis and interpretation necessitating comparison demonstrating correlation or discorrelation between the construction contract documents and actual physical site conditions. Instead, a Type II claim requires factual exploration necessary to ascertain and test the contractor's reasonable anticipations regarding future physical site conditions *Western Well Drilling Company v. United States,* 96 F.Supp. 377 (1951). Last, many times a constructor presupposes that a Type I claim is mutually exclusive of a Type II claim, and vice versa. This, however, is not the case. In fact, a Type I and II claim may be mutually inclusive, or concurrently occurring. *Kaiser Industries Corp. v. United States,* 340 F.2d 322 (Ct. Cl. 1965).

Transferring Contractual Beta

As previously discussed, the reason for shifting the risk of a differing site condition to the owner is to remove or significantly reduce the incentive to the contractor to increase contract bid price. As a result however, the project owner encounters exposure to a claim by the contractor having significant financial risk. Because by definition, a contract is a risk-transferring instrument, the owner typically drafts contractual provisions that is/are highly favorable to same, but simultaneously do not negate away the risk shifting aspect of the differing site condition provision. Typically, such contractual language creates contractual conditions maintaining three conditions precedent necessary to successfully recover an equitable adjustment to the construction contractor. These additional risk transferring contractual conditions are: a) duty to investigate site, b) exculpatory language, and c) notice requirement *Farnsworth & Chambers Co. United States,* 346 F.2d 577 (Ct. Cl. 1965). It is important to note, that such additional contractual condition(s) is/are additional provision, providing, in addition to the proof elements necessary to support a Type I or II claim, the owner with an arsenal of additional affirmative defenses to negate an equitable adjustment to contract time. Thus, not only must the contractor satisfy the six elements necessary to successfully claim a Type I change condition, or in the case of a Type II category two of the three elements listed herein, many times a contractual situation also mandates compliance with one or more of the risk transfer condition precedents discussed herein. As one may conclude, the contractor must be highly cognizant of all contractual conditions necessary to perfect a claim for equitable adjustment resulting from a changing site condition. Herein lies the import of this research paper.

The Importance of the Study

Litigation of a differing site condition provision takes place on an ex post ante basis. Typically, the contractor sues the owner under claims provision of the contract for monies concomitant the additional time and cost necessary to perform work regarding the differing site condition.

The question of critical import, is which element or elements is most often not properly evidenced and thus unproved by the contractor, thereby resulting in a disfavorable court opinion denying the contractor an equitable adjustment to contract even though the contractor otherwise has a valid claim. Therefore, the import and intent of this research study is to provide management of the construction industry with a quantitative research study that empirically measures the most often recurring deficiency in a contractor's claim for a differing site condition that otherwise found present would render the contractor a favorable court outcome.

Problem and Hypothesis Statement

A differing site condition claim between a project owner and construction contractor is the most frequent type of contractual dispute. Many times the contractor fails to favorably prevail regarding such claim owing to many reasons. This situation is exacerbated by compounding contractual language that attempts to negate the supposed purpose for incorporating a differing site condition clause in a construction contract. Failure by the contractor to comply with the technical requisites of conditions precedent at either the bidding phase of the project or during the construction phase many times negates an otherwise valid differing site condition claim for contractual equitable adjustment. Herein lies the problem for this research project. This study investigates adjudicated court decisions in the United States that have at issue the enforceability of a differing site condition claim by contractor against the federal government in a construction contract between owner and contractor. More specifically, this research seeks to answer the questions: a) which contract party interest (owner or contractor) prevails most often and, b) which element does the non-prevailing party most frequently fail to prove?

This researchable problem poses two hypothetical questions. First, whether the project owner or construction contractor statistically prevails most often regarding a differing site condition claim. The null hypothesis test is: no difference exists between whether a contractor or owner receives a favorable court award. The second hypothetical question is to statistically validate that the disfavorable court award outcome to either contracting party is either a result of pre-bid contractual administration failure, or a result of post-bid project administration in action, thus leading to the null hypothesis statement: there is no difference between the proof element frequencies and a disfavorable award and the prevailing contracting party.

Research procedure

The analytical infrastructure of this research is a non-experimental correlational study of archival case law data. The methodology employed is content analysis. The unit of analysis is court of claims' opinions and appellate level court decisions at the Federal court level involving federal government-contractor dispute regarding equitable adjustment to contract price resulting from a Type I site condition.

The search engine produced 323 cases. Of this sample size, 101 cases met research parameters concerning a construction contractor's claim for a Type I differing condition claim against the federal government. The data retrieval process was a survey instrument utilizing each Type I variable descriptor having a categorical quantitative variable property. Scalar data measure is therefore nominal using observational-interpretational classification. Each observation was recorded as a frequency count to the categorical variable displayed at Table B-1.

The dependent variable is operationally defined as favorable versus disfavorable court award to the construction contractor. The independent variable is categorically defined as each proof element, being a qualitative variable having six sub-dimensions necessary to prove a valid and enforceable Type I differing site condition claim. Because the response variable Y is a qualitative variable at two levels, and each nonresponse variable X is a qualitative variable at eight levels, the statistical technique is a multinomial non-parametric statistic. The statistical techniques utilized are the chi-square test statistic for a binomial one-way dimensional classification utilizing a 50/50 percent split distribution. The Cramer's V test for independence (strength of association between two variables) is also employed. The statistical test procedure consists of comparing observed frequencies (court decisions) with frequencies expected (50/50 percent distribution) to prove the null hypothesis. Operational descriptors for survey recordation are defined at Table B-1.

Research Results and Analysis

For data reporting and statistical manipulation purposes, the sample of cases and recordation of favorable versus disfavorable award to contractor counts were categorically inventoried according to the type of differing site condition proof element at issue in the case. Tables B-3 through B-4 present chi-square statistical test for the data recordation displayed in Table B-1.

The one-way classification matrix displayed in Table B-3 demonstrates that 30 times within the sample size of 101 cases the issue was the proof element contract documents contain indications of conditions to be encountered. These 30 observations represent 29.7 percent of the case sample. Of the 30 observations, contractor received a favorable decision 63 percent of the time, while receiving a disfavorable award 34 percent of the time. In essence, this means that the contract bid documents did not accurately reflect an actual condition experienced at the project site.

A closer inspection of the frequency counts contained in Table B-3 measured against a 50/50 split distribution provides a chi-square statistic equaling 2.134. A critical chi-square with one degree of freedom using an alpha equal to 0.01 criterion level of significance equaled 9.21. The statistical significance critical value 9.21 demonstrates that the null hypothesis cannot be rejected because the chi-square statistic value 2.134 is lesser than the chi-square critical equal to 9.21, thus suggesting that there is no numerical statistical deviation between receiving a favorable versus a disfavorable award regarding the proof element contract documents contain indications of conditions to be encountered and, there is an equally likely chance of receiving a favorable versus a disfavorable outcome regardless of the party interest. Non-rejection of the null hypothesis is the result of moderately insignificant numerical deviation between the observed frequency (f_o) and the expected frequency (f_e). This insignificant random disagreement between actual (f_o) and expected (f_e) is the result of insignificant proportional occurrence of association, meaning no association exist between a favorable or disfavorable court award, the party interest, and the particular proof element at issue.

The Cramer **V** coefficient measure equal to .266 when applied to interval of association strength 0 to +1.0, likewise demonstrates a less than moderate degree of association. Thus leading to the conclusion, there exist no statistical difference whether a contractor or owner receives a favorable versus a disfavorable award relative to this proof element. As a result, it is inconclusive as to whether the contractor is documenting or investigating worse than, or better than would be expected given a 50/50% split outcome distribution. This subconclusion thereby leads to the conclusion, that when a contractor challenges an owner regarding the proof element, contract documents contain indications of conditions to be encountered, a degree of uncertainty as to a favorable or unfavorable outcome result. This result and conclusion is a function of the categorical difference between favorable versus disfavorable outcome that occurred less frequently than would be expected from the statistical 50/50% split distribution, thereby resulting in a greater degree of chance of receiving an equally likely basis favorable award versus a disfavorable award at a probalistic level $p < 0.01$.

A review of Table B-4 demonstrates that 37 percent of the Type I cases had at issue the proof element whether the contractor acted in a reasonably prudent manner when interpreting the contract documents. The percent split was significantly disfavorable to the contractor 79% of the case observations, or alternatively the contractor favorably prevailed only 21% of the time.

For the one-way classification matrix in Table B-4, a chi-squared calculated statistic equaling 11.92 was calculated. The chi-square critical value with degrees of freedom 1, with an alpha = 0.01 criterion level of significance equaled 9.21. Because chi-square statistical is greater than chi-square critical, the null hypothesis, there is no difference between the party interests, the reasonable prudent contractor proof element at issue, and the court rendering of a favorable versus disfavorable outcome is rejected. The sub-conclusion, is that when the proof element being investigated herein is at issue, the owner significantly prevails statistically more than the contractor at a $p < 0.01$ significance level. The larger chi-square statistic at 11.92 versus the chi-square critical equal to 9.21 indicates a non-random significant statistical difference indicating a significant statistical numerical deviation from the observed (f_o) frequency and the expected probalistic frequency (f_e) for a 50/50 % statistical probalistic distribution. The Cramer V test coefficient at 0.60, on a scale of 0 to + 1.0, demonstrates that there exist a significant association and, thus a strong relationship that when X_2: the reasonable prudent contractor is at issue the owner prevails statistically significantly more often than not. In fact the owner prevails 79 percent of the time in this instance. The Cramer coefficient V clearly demonstrates that there is a strong relationship, or association in the direction owner element and a significant statistical dependency between receiving disfavorable court award and the contractor, and not proving the element act as reasonable prudence standard when interpreting and ascertaining data indicates within the contract documents.

This data result provides one with a statistically significant base to conclusively determine that the typical contractor seemingly bases a valid differing Type I claim at the pre-bid phase of the construction contracting process. Further, the data herein, seemingly suggest that the typical contractor does not completely investigate the entire set of bid documents in a timely fashion prior to bidding the contract work. These two conclusions are not exhaustive. Certainly there exist many other plausible explanations for this occurrence, and should be scientifically explored further.

Regarding variables X_3, X_4, X_5, X_6, X_7, and X_8, the sample selection did not provide an adequate number of recordable observations to conduct a probalistic examination of same that statistically would not result in a spurious empirical conclusion. However, one can, from a priori examination of Table B-2 and Table B-5, inferentially determine that there appears to be an insignificant deviation from the null hypothesis of a 50/50% split resulting in no significant statistical difference between the observed and the expected for each independent variable. Therefore, an a priori visual observation of the data would allow one to conclude no rejection of the null hypothesis is determined ascertainable and thus inconclusive regarding each proof element. The analyses of each Type I proof variable does not terminate at this juncture however. Although each variable offers no true predictive statistical measure, from a descriptive statistical basis a rational observation may be observed.

As Table B-5 and Figure 1 herein demonstrate, an X_2 proof claim appears 37% of the time, while a X_1 proof claim appears 30% of the time combining to equal 67% of case sample observation.

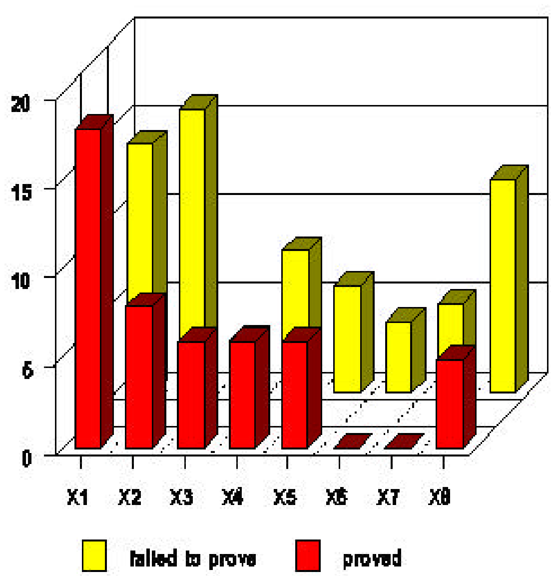

Figure. 1. Proof element frequency outcome

As Figure 1 and Table B-5 display, the other proof elements are less frequently disputed than X_1 and X_2. Further, because of X_3, X_4, X_5, X_6, X_7, and X_8 insignificant proportional observation, conjoining this with a similarly seemingly reasonable observation advanced herein that the null hypothesis for each cannot be rejected, there does appear that the contractor should allocate more resources in the direction of X_1 and X_2 at the bidding stage of the construction contracting process, thereby balancing or offsetting resource allocation to proof elements occurring during the actual construction phase.

Conclusion

Based on the data findings and analyses, the following conclusions are proffered. The majority of differing site condition complications regarding a contractual dispute between the owner and contractor occur during the bidding phase. The issue regarding whether the contractor acted in a reasonably prudent manner when interpreting the contract was the most occurring dispute element. The proof element, contract documents contain indications of conditions to be encountered, was the second highest litigious matter to appear in the study sample, followed next by the contractor must have reasonably relied on the contract indicates. As can be concluded, the most occurring or recurring proof element disputes occur at and result from the bidding phase of a construction project. Two of these proof elements, namely: a) acted in a reasonable manner, and b) reasonably relied on contract indicates, are concerned with a contractor processing of bid document indicates. The balance of the eight proof elements had some statistical presence, but did not represent a strong data presence necessary to draw a chi-square statistical inference regarding same’s import. Nevertheless, it is again interesting to note however, that the fourth most frequently recurring proof element at issue is: failure to investigate site. Here again, being a bidding phase process failure, more particularly having a strong contractual relation to the disclaiming language within the contract. The fifth most disputed proof element is actual condition encountered must be reasonably unforeseeable. This proof element bifurcates into both a bidding phase analyses and an actual construction phase question. From the partitioned conclusion of each proof element, it seems clear that a reasonable sub-conclusion is that the most recurring disputes regarding a differing site condition occurs most often at the bidding phase. A second sub-conclusion is that of the first proof elements having relative merit to these analyses, four proof element outcomes clearly demonstrated strong statistical evidence in the direction of disfavorable court awards to the contractor party in interest. Conversely, of these four proof elements, the statistical strength was in favor of the owner, thus there appears to exist a plausible inference that the contractor has failed in some respect to meet standards necessary of a bidding contractor claiming a differing condition from that presumed to exist during bidding phase examination. The study does not reach beyond this reasonable conclusion, but certainly there may, or perhaps may not, exist many other plausible explanations for the statistical findings herein. It is recommended by the researcher that this aspect of the study be continued.

The discussion turns next to whether the data clearly demonstrated a strong statistical association as presupposed by the null hypothesis. The answer is no. In general, no null hypothesis could be rejected except for the hypothesis-representing category $X_{2,}$ contractor acted in a reasonably prudent manner. The reason for the other statistical non-rejection of the null hypothesis is because the data did not demonstrate a strong independence or association in the direction reject versus non-reject on the basis of significant statistical randomization from the observed case outcome to that of the expected case outcome.

As noted herein, there is one exception however to this conclusion. The variable, contractor did act in a reasonably prudent manner, rejected the null hypothesis X_2, thereby allowing the inference that the contractor did not use reasonably prudent analyses when bidding contract indicates. The chi-square statistic and the Cramer V coefficient clearly demonstrated a strong statistical association that the owner receives a disproportion of favorable court awards relative to the proof elements, while the contractor receives a disproportional amount of disfavorable court opinions because same has failed to prove that during the bidding process the contractor did not act reasonably prudent when interpreting the contract documents. This outcome is further substantiated when conjoining or collapsing categorical partitions, thus in examining jointly two proof elements simultaneously. Here, examining jointly the categories, must act in a reasonably prudent manner, X_2 and failure to investigate site condition(s), X_8 presents an even stronger conclusion regarding reject hypothesis. For example, consider jointly categories X_2 and X_8, the case count expands to 42 case observations. This represents 42% of the case sample. In this instance, 35 cases or 83.3% of the court cases were disfavorable to the contractor, while 9 cases, or 21% of the occurrence was disfavorable to the owner. When comparing the chi-square statistic critical equal to 9.21 having degrees of freedom equaling 1 and a probability level_ 0.01, to a chi-statistic equal to 16.4 and Cramer's V coefficient equal to 0.64, there is an even stronger level of association between contractor receiving a disfavorable award and failure to use reasonable prudent conduct when examining bid document indicates. In conclusion, it is clear that court case outcomes statistically evidence that the contractor must attempt to manage the bidding process more proficiently if same expects to prevail when claiming an otherwise valid differing condition claim.

Appendix A

Table A-1 Case Law Sample

001	24 Cl. Ct. 659	A.S. McGaughan Co., Inc. v. U.S.
002	20 Cl. Ct. 184	Al Johnson Const. Co., v. U.S.
003	1979 Wl 16464	C.L. Michner, Inc. v. U.S.
004	20 Cl. Ct. 649	CCM Corp. v. U.S.
005	5 Cl. Ct. 447	Clark v. U.S.
006	18 Cl. Ct. 682	Dawco Const., Inc. v. U.S.
007	9 Cl. Ct. 302	Erickson-Shaver Contracting Corp. v. U.S.
008	7 Cl. Ct. 60	Fox v. U.S.
009	5 Cl. Ct. 662	G.M. Shupe, Inc. v. U.S.
010	1977 WL 17891	Gevyn Const. Corp. v. U.S.
011	1979 WL 16487	Gevyn Const. Corp. v. U.S.
012	36 Fed. Cl. 793	H.B. Mac, Inc. v. U.S.
013	36 Fed Cl. 347	Hardwick Bros. Co., ll v. U.S.
014	40 Fed. Cl. 184	Hoffman Const. Co. of Oregon v. U.S.
015	25 Cl. Ct. 555	Hydromar Corp. of Delaware & Eastern Seaboard Pile Driving, Inc. v. U.S.
016	23 Cl. Ct. 24	John Massman Contracting Co. v. U.S.
017	32 Fed. Cl. 647	Kit-San-Azusa, J.V. v. U.S.
018	18 Cl. Ct. 259	McCormick Const. Co., Inc. v. U.S.
019	1995 WL 908647	Olympus Corp. v. U.S.
020	98 F.3d 1314	Olympus Corp. v. U.S.
021	732 F.2d 913	P.J. Maffei Bldg. Wrecking Corp. v. U.S.
022	1981 WL 30772	Pleasant Excavating Co v. U.S.
023	31 Fed. Cl. 749	Round Place, Inc. v. U.S.
024	1980 WL 20840	Schnip Bldg. Co. v. U.S.
025	227 Ct. Cl. 148	Schnip Bldg. Co. v. U.S.
026	19 Cl. Ct. 84	Spirit Leveling Contractors v. U.S.
027	834 F.2d 1576	Stuyvesant Dredging Co. v. U.S.
028	883 F.2d 1027	Tri-Ad Constructors v. U.S.
029	220 Ct. Cl. 179	Turnkey Enterprises, Inc. v. U.S.
030	8 Cl. Ct. 42	Utility Contractors, Inc. v. U.S.
031	2 Cl. Ct. 384	Warchol Const. Co., Inc. v. U.S.
032	19 Cl. Ct. 474	Weaver-Bailey Contractors, Inc. v. U.S.
033	13 Cl. Ct. 193	Weeks Dredging & Contracting v. U.S.
034	27 Fed. Cl. 516	Youngdale & Sons Const. Co., Inc. v. U.S. - rock
035	27 Fed Cl. 516	Youngdale & Sons Const. Co., Inc. v. U.S. - water
036	ASBCA No. 20,747,83-1	Blake Const. Co.
037	GSBCA No. 4867, 77-2	Fraser Drywall
038	ASBCA No. 33576,89-3	Zenith Const.
039	ASBCA No. 27638,	Reliance Enterprises 27639,85-2
040	AGBCA No. 85-129-3, 85-218,105, P. 90,883	W.D. Kyle
041	ASBCA No. 21242, 84-2	P.J. Crowley
042	41 Fed. Cl. 303	Meyers v. U.S.
043	ASBCA No. 34672, 89-2	Futia Co.
044	PSBCA No. 3885	Thomas Young, Inc.
045	BCA at 27,181, 66-2	Lee Smith
046	312 F.2d 408	Flippian Materials
047	962 S.W. 2d	Unerstall Constr.
048	20 Ct. Cl. 725	Servidone Constr.
049	732 F.2d 918	Maffei Building
050	ASBCA No. 47733	Vecca Elect. Co.
051	ENG BCA No. PCC-117	Indelsa, S.A.
052	84 F.Supp 1021	Tobin Quarries
053	F.2d 629	Stock & Grove
054	435 F.2d 873	Foster Constr.
055	186 Ct. Cl. 398	Bolander Co.
056	ENG. BCA No. 6043	Steele Contractors
057	BCA 2323	Fisen-Meagers Const
058	1153 F.3d 1338	H.B. Mac, Inc.
059	127 F.Supp. 805	General Casualty
060	4 Cl. Ct. 46	Shea Co.
061	BCA 89-2 21,586	Dekonty
062	BCA 93-3 26,179	Glagola
063	368 F.2d 585	United Contractors
064	412 F.2d 1325	Wm. Smith Co.
065	BCA 93-3 26,172	Avisco, Inc.

066	397 F.2d 826	Morrison-Knudsen
068	49 F.3d 1070	Millgard Corp.
068	14 Cl. Ct. 242	North Slope Ltd.
069	BCA 87-3, 20,176	Zinger Const.
070	3 Cl. Ct. 353	Mojave Enters
071	237 U.S. 234	Eastern Tunneling
072	ASBCA 25697, 84-2, BCA 17, 397	Torres Const.
073	138 Ct. Cl. 571	Firhlhaber
074	AGBCA 74-103, 77-2 BCA 12,813	Southern Paving
075	BCA 2859, 69-BCA 7519	Whalen
076	186 Ct. Cl. 398	Bolander Co.
077	137 F.2d 1360	Robertson Co.
078	171 Ct. Cl. 30	Farnsworthy
079	ASBCA 18456, 74-2, BCA 10,834	Warren Painting
080	190 Ct. Cl. 546	John Vann
081	ASBCA 17474, 74-2, BCA 10, 760	Maintenance Engr.
082	ASBCA 25695, 83-2, BCA 6, 768	Commercial Mech.
083	708 F.2d 395	International Glass
084	ASBCA 26136, 83-2, BCA 16612	Leiden
085	435 F.2d 873	Foster Constr.
086	437 F.2d 1360	J.E. Robertson
087	436 F.2d 461	Pacific Alaska
088	207 Ct. Cl. 1010	Amer. Dredging
089	ASBCA 21,421,80-1, BCA 14,254	Fermin
090	ASBCA 4997, 59-1, BCA 2225	Bailey-Lewis
091	ASBCA 7876, BCA 3969	Ziskin Constr
092	ASBCA 19838, 76-2, BCA 12,104	Maverick
093	ASBCA, 450, 7802, BCA 13,537	Nineteenth
094	364 F.2d 420	Jefferson Const.
095	ASBCA 2793,70-1, BCA 8172	Piracci
096	ASBCA 19914, 781 BCA 113,128	Roy I. Strate
097	12 Cl. Ct. 328	Baltimore Constr.
098	DOI CAB 67-1, 69-2, BCA 7933	Helms Constr.
099	ENGBCA 3646, 77-1, BCA 12, 224	Exe. Const. Co.
100	PSBCA 152, 76-2, BCA 12,219	McCann Co.
101	AGBCA 307, 72-2, BCA 9475	F.H. Antrim

Appendix B

Table B-1 Case Opinion Survey Observations

Operational descriptors for survey recordation is:

where **y** = contractor: 1 = favorable court decision
2 = unfavorable court decision, and,
$\mathbf{X_1}$ = Contract documents contain indications of conditions to be encountered,
$\mathbf{X_2}$ = contractor must act in a reasonably prudent manner when interpreting contract documents,
$\mathbf{X_3}$ = the contractor must have reasonably relied on the contract indications,
$\mathbf{X_4}$ = conditions actually encountered differ materially from those indicated in the contract documents,
$\mathbf{X_5}$ = Actual conditions encountered must be reasonably unforeseeable,
$\mathbf{X_6}$ = proper notice not timely filed,
$\mathbf{X_7}$ = exculpatory/disclaiming contractual language,
$\mathbf{X_8}$ = failure to investigate site,
where X_i......X_n = 0 = failed to prove
1 = proved

Case X Claim Proof Elements									
#	**Outcome**	$\mathbf{X_1}$	$\mathbf{X_2}$	$\mathbf{X_3}$	$\mathbf{X_4}$	$\mathbf{X_5}$	$\mathbf{X_6}$	$\mathbf{X_7}$	$\mathbf{X_8}$
001	2	0							
002	2				0				
003	1	1							
004	1	1							
005	2					0			
006	1		1						
007	2				0				
008	2		0						
009	2				0				
010	1	1							
011	1	1							
012	1		1						
013	2	0							
014	2					0			
015	2				0				
016	2		0						
017	1	1							
018	2					0			
019	2	0							
020	2	0							
021	2	0							
022	2								0
023	2				0				
024	2						0		
025	2						0		
026	2					0			
027	2								0
028	1	1							
029	2				0				
030	2				0				

031	2				0				
032	1	1							
033	2		0						
034	2								0
035	2	0							
036	2	0							
037	2		0						
038	2			0					
039	1		1						
040	2	0							
041	1	1							
042	2		0						
043	2			0					
044	2		0						
045	2		0						
046	2		0						
047	1								
048	1	1							
049	1				1				
050	2		0						
051	2		0						
052	1	1							
053	1	1							
054	1	1							
055	1				1				
056	2		0						
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058	1				1				
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061	1	1							
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065	2		0						
066	1	1							
067	2								0
068	2		0						
069	2		0						
070	2			0					
071	1			1					
072	2		0						
073	1				1				
074	2		0						
075	2		0						
076	2		0						
077	1		1						
078	2		0						
079	1		1						

080	1			1					
081	2								1
082	1		1						
083	1	1							
084	2	1							
085	2	0							
086	1	1							
087	1	1							
088	2		0						
089	1				1				
090	2		0						
091	1		1						
092	2		0						
093	2		0						
094	2		0						
095	2		0						
096	2		0						
097	1		1						
098	2	0							
099	1	1							
100	1					1			
101	2								0

Table B-2

Frequency Distribution for a Type I Differing Site Condition Claim: Proof Elements

COURT

Opinion	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	TOTAL
Favorable	19	8	3	5	1	0	0	1	37
CONTRACTOR									
Disfavorable	11	29	3	8	5	2	0	6	64

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Dynamic Prediction of Traffic Flow and Congestion at Freeway Construction Zones

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It is often necessary to establish construction zones on roadways for pavement and bridge repair and rehabilitation activities. A construction zone reduces the number of lanes available for traveling vehicles and therefore forms a bottleneck section for traffic flow. The ability of dynamically predicting traffic flow rates with real-time data is essential for both highway engineers and construction contractors. For highway engineers, the predicted values of traffic flow rates could be utilized to maintain smooth traffic flows at construction zones. It would enable them to apply traffic control measures to prevent traffic congestion at construction zones rather than to deal with traffic problems after traffic congestion already occurred. For contractors, knowing the future traffic conditions around construction zones would be great advantageous in scheduling construction activities and equipment movements. It was found in this study that using the Kalman predictor in combination with the first-order autoregressive time series provided satisfactory dynamic predictions of construction zone traffic flow. A prediction of traffic flow at a construction zone also constitutes a prediction of traffic congestion if the traffic capacity of the construction zone is known. If the predicted traffic flow rate is equal to or greater than the traffic capacity, then traffic congestion is expected in the coming time period and appropriate traffic control actions can be taken to prevent the traffic congestion.

Key Words: Dynamic Prediction, Traffic Flow, Congestion, Work Zone, Time Series, Kalman

Introduction

It is often necessary to establish construction zones on roadways for pavement and bridge repair and rehabilitation activities. A construction zone reduces the number of lanes available for traveling vehicles and therefore forms a bottleneck section for traffic flow. Traffic congestion occurs at a construction zone when traffic flow exceeds the capacity of the construction zone. Consequently, during congestion vehicles go through the construction zone at reduced speeds and with fluctuated traffic flow rates (Jiang, 1999). Vehicles on the roadway, including construction vehicles that haul construction materials to or from the construction zone, endure considerably greater traffic delays at the construction zone under congested traffic conditions than under uncongested conditions. Therefore, the ability of dynamically predicting traffic flow rates with real-time data is essential for both highway engineers and construction contractors. For highway engineers, the predicted values of traffic flow rates could be utilized to maintain smooth traffic flows at construction zones. It would enable them to apply traffic control measures to prevent traffic congestion at construction zones rather than to deal with traffic problems after traffic congestion already occurred. For contractors, knowing the future traffic conditions around construction zones would be great advantageous in scheduling construction activities and equipment movements. As traffic flow is maintained smooth and traffic congestion is prevented, the safety of the motorists and construction workers can be improved.

Several methods of adaptive traffic forecasting have been explored by researchers. Ahmed and Cook (1982) applied the time series methods to provide short-term forecast of traffic occupancies for incident detection. Okutani and Stephanedes (1984) employed the Kalman filtering theory in dynamic prediction of traffic flow. Davis et al. (1990) used pattern recognition algorithms to forecast freeway traffic congestion. Lu (1990) developed a model of adaptive prediction of traffic flow based on the least-mean-square algorithm. As part of the effort to improve traffic control at construction zones, this study applied the time series theory and Kalman filtering theory to adaptively predict traffic flow at the construction zones on Indiana's freeways with real-time data. It was found that using the Kalman predictor in combination with the autoregressive process of time series could provide satisfactory dynamic predictions of construction zone traffic flow. As traffic capacity values of Indiana's freeway construction zones were determined (Jiang, 1999), a prediction of traffic flow also constitutes a prediction of traffic congestion. If the predicted traffic flow rate is equal to or greater than the traffic capacity, traffic congestion is expected in the coming time period and appropriate traffic control actions can be taken to prevent the traffic congestion.

Construction Zone Types and Data Collection

Construction zone is defined in the 1994 Highway Capacity Manual (TRB, 1994) as "an area of highway in which maintenance and construction operations are taking place that impinge on the number of lanes available to moving traffic or affect the operational characteristics of traffic flowing through the area". This study focused on the two types of construction zones used on Indiana's four-lane divided highways, as shown in Figures 1 and 2 and defined as follows (FHWA, 1989):

1. Partial Closure (or single lane closure) - when one lane in one direction is closed, resulting in little or no disruption to traffic in the opposite direction.
2. Crossover (or two-lane two-way traffic operations) - when one roadway is closed and the traffic, which normally uses that roadway, is crossed over the median, and two-way traffic is maintained on the other roadway.

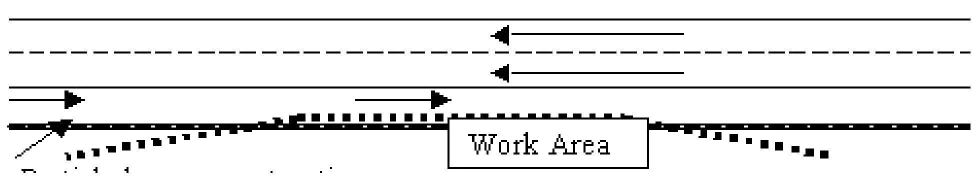

Figure 1. Partial closure construction zone.

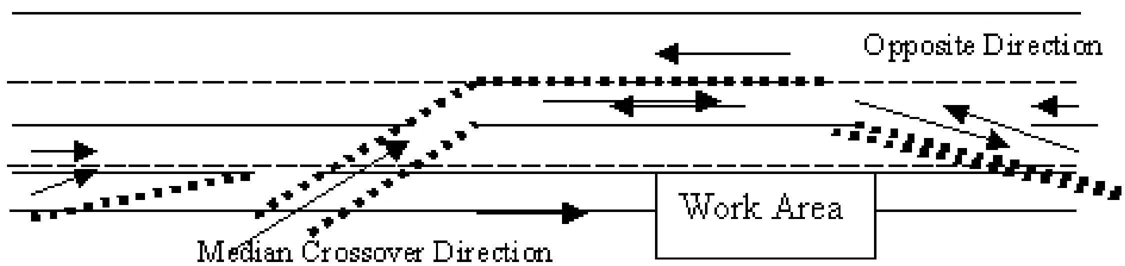

Figure 2. Crossover construction zone.

Traffic data at select construction zones on interstate highway sections was collected between October 1995 and April 1997. Traffic counters with road tubes were used for data collection. Traffic volume, vehicle speed and classification were recorded in order of time series. The vehicle counters were set up to classify the detected vehicles into three groups: 1). passenger cars, 2) heavy trucks and 3) buses. To express traffic flow in passenger cars per hour, the traffic flow rate was converted to hourly volume and the adjustment factors from the 1994 Highway Capacity Manual were used to convert trucks and buses to passenger car equivalents.

Prediction of Traffic Flow Using Time Series

Based on the collected traffic data, the traffic capacity values were determined (Jiang, 1999) for four types of construction zone layouts on Indiana four-lane freeways, i.e., crossover construction zone in the opposite direction, crossover construction zone in the crossover direction, partial closure with right lane closed, and partial closure construction zone with left lane closed. Table 1 presents the four construction zone capacity values obtained with traffic data at construction zones on Indiana four-lane freeways (Jiang, 1999).

Table 1

Traffic Capacities of Construction Zones on Indiana's Four-Lane Freeways

Construction Zone Type	Traffic Capacity
Crossover (Opposite Direction)	1745 Passenger Cars Per Hour
Crossover (Crossover Direction)	1612 Passenger Cars Per Hour
Partial Closure (Right Lane Closed)	1537 Passenger Cars Per Hour
Partial Closure (Left Lane Closed)	1521 Passenger Cars Per Hour

Given the construction zone capacity values, it was desired to develop methods to predict traffic flow and congestion at construction zones so that appropriate traffic control strategies could be applied to avoid traffic congestion and to reduce traffic delay. Traffic flow rate constantly changes with time on any given highway sections. To predict traffic conditions, the relationship between traffic flow and time must be studied. The time series theory (Cryer 1986, Bowerman and O'Connell, 1979) is a frequently used tool to study the traffic and time relationship. One of the time series models is the *autoregressive process* $\{Z(t)\}$. A *p*th-order autoregressive process, AR(p), satisfies the following equation:

$$Z(t) = \phi_1 Z(t-1) + \phi_2 Z(t-2) + \cdots + \phi_p Z(t-p) + \varepsilon_t \qquad (1)$$

where:

$Z(t)$ = value of the process Z at time t;

ϕ_i = unknown parameters; i = 1, 2, 3, …, p

ε_t = a random variable with zero mean and variance σ_w^2.

This equation requires that the mean of the series has been subtracted out so that *Z(t)* has a zero mean (Cryer, 1986). This time series implies that the current value of the series *Z(t)* is a linear combination of the *p* most recent past values of itself plus an error term ε_t.

To show the use of the time series method in traffic flow prediction, the recorded traffic flow data at a construction zone on Interstate 65 over Indiana's State Road 46 was selected for fitting the first-order autoregressive process model. It was a crossover construction zone for bridge rehabilitation. The traffic flow data was collected inside the construction zone in the crossover direction at 10-minute intervals from 4:00 a.m. to noon on November 2, 1996. Figure 3 shows the observed traffic flow rates in order of time. With the traffic flow data at this construction zone, an AR(1) model was fitted using the Minitab (1996) software. The AR(1) equation for the traffic flow rate is expressed as follows:

$$f(t) = \phi_1 f(t-1) + \varepsilon_t \qquad (2)$$

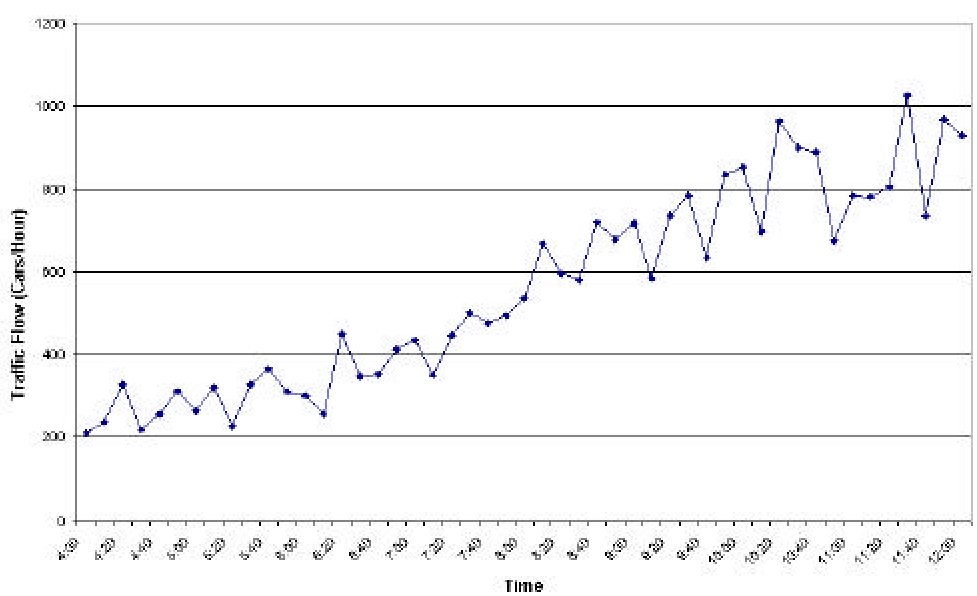

Figure 3. Observed construction zone traffic flow.

In Equation 2, *f(t)* denotes the traffic flow rate at time t. As expressed by the equation, the traffic flow rate at time t, *f(t)*, can be predicted from the traffic flow rate observed at the most recent past time point t-1, *f(t-1)*. It should be noted that the mean of the series of traffic flow rates must be subtracted from *f(t)* as required by the autoregressive model of Equation 1. The actual prediction is then the calculated *f(t)* plus the mean. If *f(t-1)* is given, then *f(t)* can be predicted as:

$$\hat{f}(t \mid t-1) = \bar{\phi}_1 f(t-1) \qquad (3)$$

In this equation, $\bar{\phi}_1$ is the estimate of ϕ_1, and $\hat{f}(t \mid t-1)$ is the predicted value of $f(t)$ based on the most recent observed traffic flow rate, $f(t\text{-}1)$. Through this equation, predictions of traffic flow rates at the given construction zone were calculated from 4:00 a.m. to noon at 10-minute intervals. For comparison, plotted in Figure 4 are the predicted and observed values of the traffic flow rates.

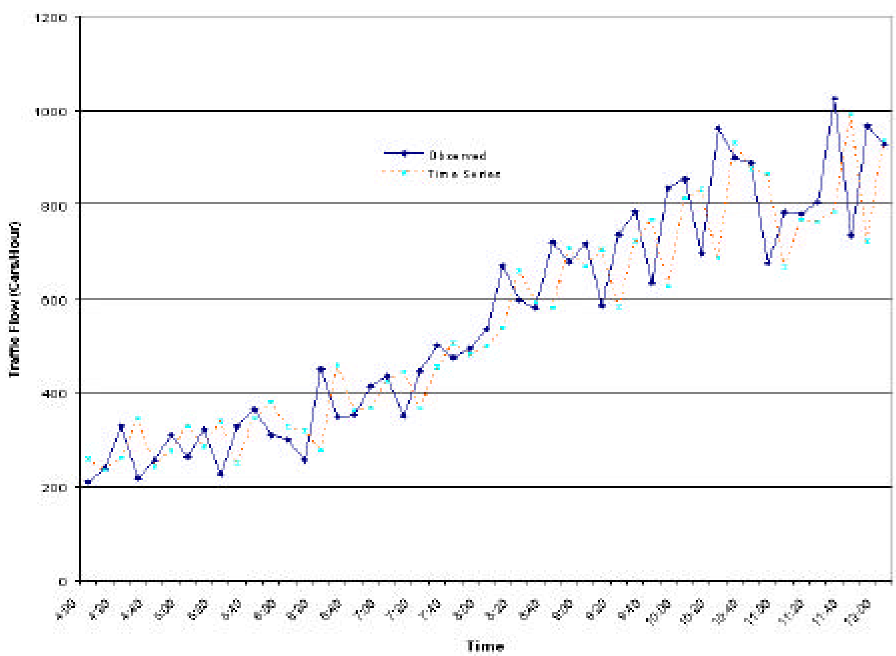

Figure 4. Observed and time series predicted traffic flow rates.

The curves in Figure 4 indicate that the predicted values followed the patterns of the observed traffic flows. The accuracy of the time series predictions is reflected by the values of residuals. In this case, a residual is the difference between the observed traffic flow rate and the traffic flow rate predicted by the time series model, that is, residual = $f(t) - \hat{f}(t \mid t-1)$. The residuals of the time series predictions are listed in Appendix A for all data points during the eight-hour period. To examine the magnitudes of the residuals, the absolute values of the residuals were used to calculate the statistics. As shown in Appendix A, the absolute values of residuals have a mean of 83.9, a standard deviation of 72.9, and a minimum of 1.7, and a maximum of 276.1. Although these values are not extremely unacceptable, they certainly suggest the needs for improvement in the accuracy of the time series predictions.

Prediction of Traffic Flow Using Kalman Predictor in Combination with Time Series

One of the applications of control theory is to use the Kalman predictor (Bozic, 1979) in recursive predictions of random signal processes. For example, the signal model can be a first-order autoregressive process:

$$x(t+1) = a\,x(t) + w_t \qquad (4)$$

The observation (or measurement) is affected by additive random error v_t:

$$y(t) = c\,x(t) + v_t \qquad (5)$$

where:

v_t is a random variable with zero mean and variance σ_v^2 .

The Kalman predictor for the above signal model can be expressed as follows:

Predictor equation:

$$\hat{x}(t+1\,|\,t) = a\,\hat{x}(t\,|\,t-1) + k(t)[y(t) - c\hat{x}(t\,|\,t-1)] \qquad (6)$$

Predictor gain:

$$k(t) = \frac{acp(t\,|\,t-1)}{c^2 p(t\,|\,t-1) + \sigma_v^2} \qquad (7)$$

Prediction mean-square error:

$$p(t+1\,|\,t) = \frac{a}{c}k(t)\sigma_v^2 + \sigma_w^2 \qquad (8)$$

Equations 6, 7 and 8 are called one-step Kalman predictor of the signal process expressed by Equations 4 and 5. The Kalman method yields the estimate of *x(t + 1)*, i.e. the signal at time t+1, given the measured data *x(t)* and the previous estimate $\hat{x}(t\,|\,t-1)$ at time t. It can be proved (Bozic, 1979) that this one-step prediction estimate, denoted as $\hat{x}(t+1\,|\,t)$, is an optimum estimate because the Kalman recursive prediction process minimizes the mean-square prediction error $E[x(t+1) - \hat{x}(t+1\,|\,t)]^2$.

Some features of the Kalman predictor, such as recursive, continuously incorporating the most recent real-time data, and optimum prediction, are exactly the desirable functions for an efficient traffic flow prediction model. To use the Kalman predictor in traffic flow prediction, the AR(1) time series model as in Equation 2 can be used as the traffic flow model, that is:

$$f(t+1) = \phi\,f(t) + \varepsilon_t \qquad (9)$$

Equation 9 is the first-order autoregressive process for the traffic flow. In addition, the observation (or measurement) of the traffic flow, m(t), is affected by additive random error v_t:

$$m(t) = \beta f(t) + v_t \qquad (10)$$

Equation 10 is related to the accuracy of the traffic data measurement devices used in data collection. The one step Kalman recursive prediction equations can then be readily obtained from Equations 6 through 8:

Predictor equation:

$$\hat{f}(t+1 \mid t) = \phi \hat{f}(t \mid t-1) + k(t)[m(t) - \beta \hat{f}(t \mid t-1)] \qquad (11)$$

Predictor gain:

$$k(t) = \frac{\phi \beta p(t \mid t-1)}{\beta^2 p(t \mid t-1) + \sigma_v^2} \qquad (12)$$

Prediction mean-square error:

$$p(t+1 \mid t) = \frac{\phi}{\beta} k(t) \sigma_v^2 + \sigma_\varepsilon^2 \qquad (13)$$

With Equations 9 through 13, traffic flow rate at t+1, $f(t+1)$, can be predicted as $\hat{f}(t+1 \mid t)$ for each observed data at time t, $f(t)$. Since Equation 9 is a time series model of the first order autoregressive process, this Kalman predictor model is a combination of the time series and the Kalman predictor. It was expected that this prediction model would improve the prediction accuracy over the time series model as defined in Equation 2. To verify this, the Kalman predictor model was also applied to the construction zone traffic flow data described in Figure 3. The predicted traffic flow rates from the Kalman predictor along with the corresponding observed values and the values from the time series method are plotted in Figure 5.

As shown in the figure, most of the predicted values from the Kalman model are closer to the observed values than the predicted values from the time series model. This indicates that the Kalman method indeed improved the prediction accuracy over the time series method. The differences in the prediction accuracy of the two methods can be more clearly described by plotting their corresponding residual values into the same graph, as shown in Figure 6. The residual graph distinctly shows that the most residuals of the Kalman predictions are considerably smaller than those of the time series predictions. Therefore, the improvement of the Kalman predictor over the time series method in traffic flow prediction is apparent and significant.

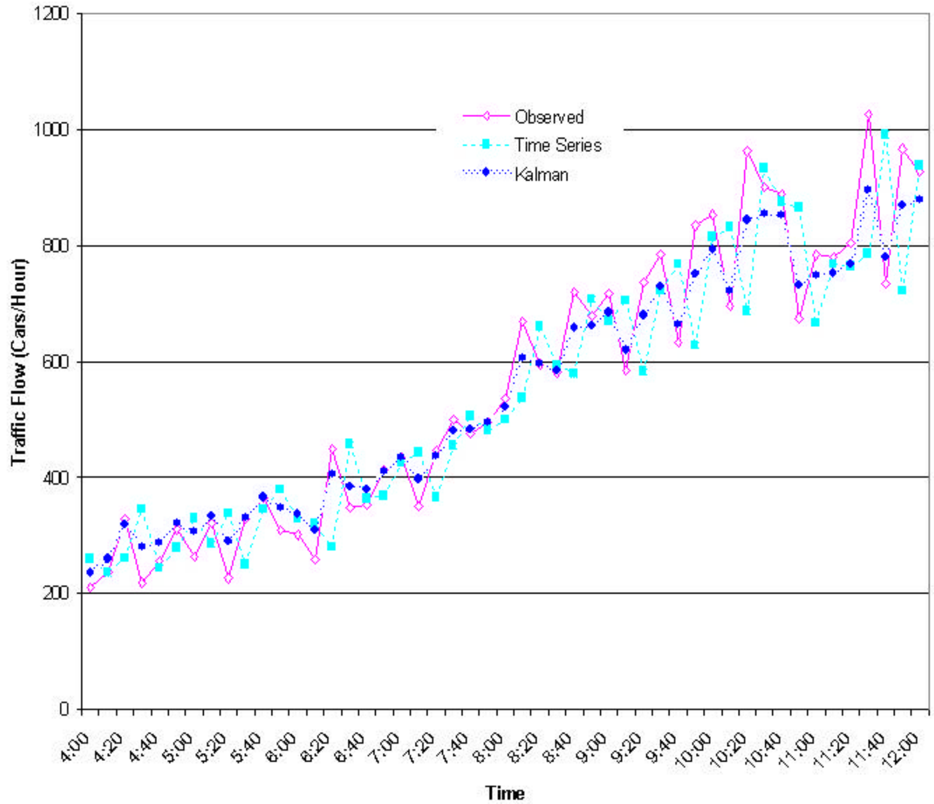

Figure 5. Observed and Kalman and time series predicted traffic flow rates.

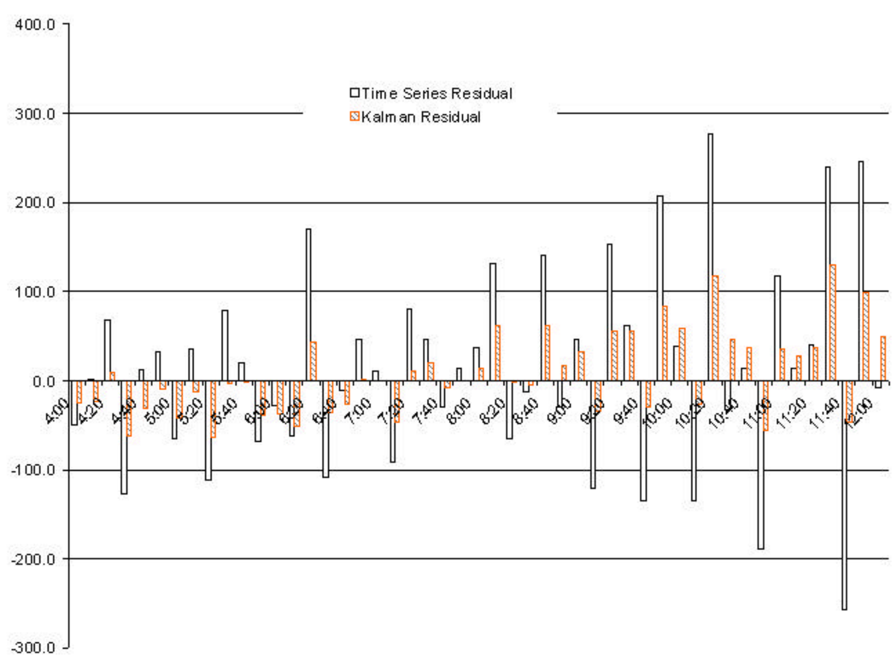

Figure 6. Residuals of Kalman predictor and time series predictions.

For a quantitative comparison, the values of the observed and predicted traffic flow rates are presented in Appendix B with the corresponding residual values. In addition, the differences between the absolute values of the time series and Kalman residuals are also included in the table. Because there are positive and negative residuals, the use of the absolute values of the residuals is to compare the magnitudes of the residuals from the two prediction methods. The magnitude of a residual is the difference between the observed value and the predicted value. Therefore, a more accurate prediction yields a smaller magnitude of residual. Ifthe absolute value of time series residual (TR) minus the absolute of Kalman residual (KR) is positive, i.e., abs(TR)-abs(KR) > 0, then the magnitude of time series residual is greater than the Kalman residual, indicating the time series prediction is less accurate than the Kalman prediction.

As shown in the last column of Appendix B, there are 40 positive values and 9 negative values of abs (TR)-abs (KR). This indicates that 40 out of the 49 Kalman predictions are more accurate than the time series predictions. The statistics of the absolute values of residual were also calculated for the predictions from the two methods. As shown in Appendix B, the Kalman predictions have smaller values of mean, standard deviation, minimum and maximum of the absolute residuals than the time series predictions. Compared to the time series predictions, the Kalman predictions reduced the mean of the absolute residual values by (83.9-37.1)/83.9=55.8% and the standard deviation by (72.9-29.0)/72.9=60.2%. These large reductions in the values of the mean and standard deviation represent a significant improvement in the traffic flow predictions.

To statistically compare the predictions of the two methods, a paired t-test was performed. Since a t-test requires the data follow a normal distribution, the Anderson-Darling normality test (Minitab, 1996) was used to check if the absolute values of the residuals follow a normal distribution. The normality test resulted in a p-value of 0.000 for the absolute values of the time series residuals and a p-value of 0.015 for the absolute values of the Kalman residuals, indicating neither of the data sets follows a normal distribution at a level of $\alpha = 0.05$. Then the data sets were transformed by square root of the absolute values of the residuals, i.e., $r'_{1i} = \sqrt{abs(TR)}$ and $r'_{2i} = \sqrt{abs(KR)}$. The Anderson-Darling normality test on the transferred data yielded a p-value of 0.135 for r_{1i} and a p-value of 0.175 for r_{2i}. Therefore, both of the transformed data sets are normally distributed at a level of α = 0.05 and the paired t-test can be applied to compare them. The paired t-test was used to test if the difference between the mean of r_{1i} (μ_2) and the mean of r'_{2i} (? $_2$) is zero or greater than zero. The hypotheses to be tested are as f ollows:

H_0: $\mu_1 - \mu_2 > 0$

H_a: $\mu_1 - \mu_2 > 0$

If the Type I error is controlled at α = 0.05, then the p-value of the paired t-test can be compared to the α value according to the decision rule:

If p-value $\geq \alpha$, conclude H_0.
If p-value $< \alpha$, conclude H_a.

The p-value of the paired t-test is 0.000, which is less than ? ? 0.05. Therefore, H_a is concluded, i.e., the mean difference is greater than zero or μ_1 is significantly greater than μ_2. This implies that the Kalman predictor in combination with the time series method provides much better predictions of traffic flow rates than the time series method.

Prediction of Traffic Congestion

Once the traffic capacity of a construction zone is known, the dynamic prediction of traffic flow rates discussed above constitutes a dynamic prediction of traffic congestion at the construction zone. As previously indicated, the traffic data used in the above example was collected at a crossover construction zone in the crossover direction. From Table 1, it can be found that the traffic capacity of this type of construction zone in Indiana is 1612 passenger cars per hour. Thus, the traffic congestion at this construction zone can be predicted with the Kalman predictor method at each step of the prediction according to the following criteria:

If $\hat{f}(t+1|t) < 1612$ passenger cars per hour, then no congestion at time t+1 is predicted;
If $\hat{f}(t+1|t) \geq 1612$ passenger cars per hour, then congestion at time t+1 is predicted.

Conclusions

This study showed that using Kalman predictor in combination with the first-order autoregressive process of time series provided significantly improved traffic flow predictions over using only the time series method. This Kalman predictor model can predict traffic flow at construction zones dynamically with newly available traffic data at specified time intervals. Therefore, it can be used as an efficient tool for real-time construction zone traffic control and can be applied in such areas as highway construction planning and scheduling. A dynamic prediction of traffic flow rate at a construction zone with the Kalman predictor constitutes a dynamic prediction of traffic congestion as long as the traffic capacity at the construction zone is known.

Acknowledgments

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Appendix A

Comparison of Observed and Time Series Predicted Traffic Flow Rates

	Observed = $f(t)$	Time Series = $\hat{f}(t \mid t ? 1)$	Residual = $f(t)$- $\hat{f}(t \mid t ? 1)$
4:00	210	258.8	-48.8
4:10	237	235.3	1.7
4:20	328	260.4	67.4
4:30	218	344.6	-126.2
4:40	256	243.1	12.7
4:50	311	277.8	33.0
5:00	264	328.7	-65.0
5:10	321	285.1	35.4
5:20	226	337.8	-112.2
5:30	328	249.8	78.2
5:40	364	344.7	19.7
5:50	310	378.5	-69.0
6:00	300	327.6	-27.4
6:10	257	319.0	-61.8
6:20	449	279.0	169.9
6:30	348	456.7	-108.6
6:40	352	363.4	-11.2
6:50	413	367.1	46.1
7:00	434	423.7	10.4
7:10	351	443.0	-92.2
7:20	446	365.9	80.2
7:30	501	454.1	46.5
7:40	475	504.6	-29.3
7:50	494	481.3	13.1
8:00	535	498.9	36.3
8:10	668	536.7	131.7
8:20	595	660.2	-65.0
8:30	581	592.4	-11.9
8:40	719	578.8	140.3
8:50	678	707.2	-29.0
9:00	716	669.3	46.9
9:10	585	704.5	-119.9
9:20	736	582.6	153.3
9:30	784	722.8	61.6
9:40	633	767.6	-134.4
9:50	834	627.6	206.8
10:00	853	814.1	39.1
10:20	962	686.2	276.1
10:30	900	932.6	-32.6
10:40	889	874.9	13.8
10:50	675	864.3	-189.5
11:00	784	666.1	117.6
11:10	780	767.1	13.1
11:20	804	763.8	40.1
11:30	1026	785.8	239.9
11:40	735	991.4	-256.9
11:50	967	721.5	245.6
12:00	929	937.0	-8.4

Statistics of absolute values of residuals:

Mean=83.9 Standard Deviation = 72.9

Minimum = 1.7 Maximum = 276.1

Appendix B

Results of Time Series and Kalman Predictions

Time	Observed	Time Series	Kalman	Time-Series Residual (TR)	Kalman Residual (KR)	Abs(TR)-Abs(KR)
4:00	210	258.8	235.4	-48.8	-25.4	23.5
4:10	237	235.3	259.6	1.7	-22.6	-20.8
4:20	328	260.4	318.6	67.4	9.3	58.1
4:30	218	344.6	280.2	-126.2	-61.8	64.4
4:40	256	243.1	286.8	12.7	-31.0	-18.3
4:50	311	277.8	319.9	33.0	-9.1	23.8
5:00	264	328.7	305.8	-65.0	-42.1	22.9
5:10	321	285.1	332.4	35.4	-11.8	23.6
5:20	226	337.8	289.1	-112.2	-63.5	48.7
5:30	328	249.8	330.4	78.2	-2.4	75.8
5:40	364	344.7	366.0	19.7	-1.5	18.2
5:50	310	378.5	348.4	-69.0	-38.9	30.1
6:00	300	327.6	336.7	-27.4	-36.5	-9.1
6:10	257	319.0	308.3	-61.8	-51.2	10.6
6:20	449	279.0	405.0	169.9	43.9	126.0
6:30	348	456.7	384.3	-108.6	-36.2	72.4
6:40	352	363.4	379.0	-11.2	-26.8	-15.6
6:50	413	367.1	411.1	46.1	2.2	44.0
7:00	434	423.7	434.6	10.4	-0.5	9.9
7:10	351	443.0	396.7	-92.2	-45.9	46.3
7:20	446	365.9	436.0	80.2	10.1	70.1
7:30	501	454.1	480.9	46.5	19.7	26.7
7:40	475	504.6	483.3	-29.3	-7.9	21.3
7:50	494	481.3	494.8	13.1	-0.5	12.6
8:00	535	498.9	521.9	36.3	13.3	23.0
8:10	668	536.7	606.3	131.7	62.2	69.6
8:20	595	660.2	596.5	-65.0	-1.2	63.8
8:30	581	592.4	584.6	-11.9	-4.1	7.8
8:40	719	578.8	657.7	140.3	61.4	78.9
8:50	678	707.2	661.7	-29.0	16.5	12.5
9:00	716	669.3	684.5	46.9	31.8	15.2
9:10	585	704.5	619.3	-119.9	-34.7	85.2
9:20	736	582.6	679.8	153.3	56.1	97.3
9:30	784	722.8	729.2	61.6	55.2	6.4
9:40	633	767.6	662.9	-134.4	-29.7	104.7
10:00	853	814.1	793.8	39.1	59.4	-20.3
10:10	696	831.4	722.0	-135.0	-25.6	109.4
10:20	962	686.2	844.2	276.1	118.2	157.9
10:30	900	932.6	854.3	-32.6	45.7	-13.1
10:40	889	874.9	851.7	13.8	37.0	-23.2
10:50	675	864.3	731.2	-189.5	-56.4	133.1
11:00	784	666.1	747.8	117.6	36.0	81.6
11:10	780	767.1	751.9	13.1	28.3	-15.2
11:20	804	763.8	766.7	40.1	37.3	2.8
11:30	1026	785.8	896.0	239.9	129.7	110.2
11:40	735	991.4	780.9	-256.9	-46.4	210.5
11:50	967	721.5	868.5	245.6	98.6	147.0
12:00	929	937.0	879.2	-8.4	49.4	-41.0

Statistics of absolute values of residuals:

	Time Series	Kalman
Mean	83.9	37.1
Standard Deviation	72.9	29.0
Minimum	1.7	0.47
Maximum	276.1	129.7

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A General Characterization of Pavement System Failures, with Emphasis on a Method for Selecting a Repair Process

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This article provides an overview of pavement system failures; their potential causes and identifies a method for selecting a final repair process.

Keywords: Pavement, Pavement Performance, Highway Engineering, and Roads

Introduction

Regardless of the care exercised in planning, design, construction and maintenance of a pavement section, it will ultimately fail. It is when the failure occurs unexpectedly or prematurely that those involved in the planning, design, construction and maintenance of pavement sections are left to search for the causes and prevention of premature pavement failures and the resulting economic impact. Although the most common result of pavement failure is economic loss, a failure can result in a significant detriment to the lives and safety of passengers.

The primary purpose of a pavement section is to convey vehicles in a dependable manner for a designated period of time and provide both safety and comfort to the passenger. This simplistic task becomes a difficult problem to solve when factors of variable traffic frequency and load, variable pavement and subgrade materials, maintenance serviceability, the environment and economy are considered. It is these factors, which make the awareness of premature pavement failure, its causes, results and cures so important.

Definition

A pavement section may be generally defined as the structural material placed above a subgrade layer. In flexible pavement sections (asphaltic concrete) this is typically a multi-layer system composed of stabilization layer, base and surface layers each of which may be further subdivided. Subgrades are also considered as layers in pavement design with their thickness assumed to be infinite and their materials characteristics assumed to be unchanged or unmodified. Rigid pavement sections consist of portland cement concrete placed on a prepared base (usually called a subbase) or directly on the subgrade. Composite pavement sections consist of combinations of various sections of rigid and flexible pavements. Examples of this include asphaltic concrete overlays of rigid pavements and the use of rigid or semi-rigid base or subbase components such as soil-cement or cement treated materials in a flexible pavement section.

Failures

Although in a sense all pavement failures are functional failures, assigning failure categories makes the understanding of a failure somewhat easier. In a broad sense, failures may be categorized as structural, functional or materials failures. Certainly, these categories may overlap and the failure result from, or be contributed to, by one or more of the categories. Structural failure may be defined as the loss of load carrying capability of the pavement section resulting in the need for significant repair or replacement. A functional failure is a broader term, which may include the loss of any function of the pavement such as skid resistance, structural capacity, and serviceability or passenger comfort. A materials failure is the disintegration or loss of material characteristics of any of the component materials.

Early indications of pavement failure are not always available. Physical evidence of a failure is often too little, too late and significant, costly damage is already well on its way. Before the use of nondestructive testing became practical and economical, physical surveys were the primary means of failure discovery and failure prediction. Physical surveys supplemented by nondestructive examination and analyses are a common tool in the evaluation and characterization of a pavement system. Physical surveys that are most commonly used include those set up to provide the AASHTO Present Serviceability Index (PSI) for highway pavements and the Pavement Condition Index (PCI) for airfield pavements and highway pavements.

There is physical evidence available for each type of pavement failure. These manifestations of distress may be broadly classified as **cracking, distortion, disintegration and skid resistance**. In rigid or portland cement concrete pavements, cracking and disintegration are prominent forms of distress while in asphaltic concrete surfaces distortion (rutting, shoving), disintegration (raveling) and cracking (alligator, reflective) are relatively common.

Cracks in rigid pavements may be either traffic load induced, thermally induced, caused by chemical instability, caused by mix characteristics or by construction technique. These cracks vary in manifestation from slight crazing of the surface to full depth structural cracking causing loss of structural integrity. In assessing crack distress of concrete pavements it is important to recognize the relationships between the location and orientation of the cracking to its failure category. For example, crazing or map cracking is typically categorized as a materials or technique problem that, while affecting durability, has a little or no bearing on the structural integrity of the section, whereas large corner cracks in slab sections are significant structural problems.

Cracks in flexible pavement sections may be load induced fatigue, reflective (from cracks in the base), shrinkage or caused by a deficient mix design. Each type of crack shows up in a particular manner, for instance load induced cracks typically start as longitudinal cracks and progress to alligator cracking. Reflective cracks typically follow the shrinkage crack or joint pattern of the base material.

Distortion of pavement sections is defined as a change in the surface plane of the pavement resulting from post-construction compaction or consolidation, settlement, heave, shoving, or slab curl. Distortions seriously affect the riding quality of a pavement and are the items most often causing rider complaints.

Disintegration of the component materials can occur in rigid, flexible and composite pavement sections for a variety of reasons. Most disintegration problems are traceable to materials or mixture deficiencies.

Disintegration may include chemical reactions that can occur between cement and aggregates (alkali-silica or alkali-carbonate reactions), between the aggregate and groundwater (dissolving of carbonate aggregates in acidic groundwater), between the cement and groundwater (sulphate attack) and between or among other constituents. Chemical reactions range in severity from minor to major where entire pavement sections are required to be removed and replaced due to chemical instability of the components. Deficiencies in the mix proportions of both the asphaltic concrete and portland cement concrete can lead to severe disintegration in the form of raveling, scaling and spalling.

Loss of Skid Resistance is one of the most serious of pavement failures. This creates a significant detriment to the safety of the riding public. Loss of skid resistance may be caused by poor quality aggregate or aggregate that does not have adequate angularity, bleeding or flushing of an asphalt surface and the deposition of contaminants onto the surface.

A peripheral but equally important consideration in pavement failures is the drainage of the pavement system. Drainage can affect each category of pavement failure but typically affects the structural integrity and the skid resistance. Inadequate or improper drainage may cause materials characteristics of otherwise stable materials to become very unstable under load and thus create a variety of problems including potholes, depressions, and edge pumping and cracking. In the investigation of pavement failures, drainage must be considered.

Method for Selecting a Repair Process

Each type of pavement failure can be solved. The solutions may range from doing little or nothing and simply being aware that a potential problem exists to removal and replacement of an entire system. Both ends of the spectrum can prove to be quite costly. The key to solving pavement problems or failures is to follow a logical method for selecting an appropriate repair process.

Selecting an appropriate repair process or method will normally involve at least the following steps:

1. Identify/ classify anomalies, then thoroughly investigate and identify each failure aspect and analyze its cause
2. Identify system constraints such as traffic routing, funds, or other.
3. Perform literature/ information search.
4. Compare probable materials and techniques to system constraints.
5. Test the indicated materials.

6. Perform economic analysis.
7. Select and recommend appropriate materials and techniques to restore the pavement to serviceability.

It is imperative that each of the noted steps be compared to the issue at hand and applied in its appropriate context. As an example, if a pothole is a result of a petroleum spill on the surface of an asphaltic concrete pavement, then steps should be taken to mitigate petroleum spills, and only secondarily should consideration be given to changing the pavement design in an attempt to compensate for the probability of a future petroleum spill.

Materials, Techniques and Applications

Repair and rehabilitation are currently being performed all over the country to varying extents and with significantly variable success. Many techniques are being used and the list of materials employed is quite extensive. The unfortunate aspect of the existingtechnology is that there is little or no uniformity in materials, processes and technique and even fewer published guidelines for the initiation of such tasks. In short, procedural training and a concise application manual are greatly needed.

While many professional, technical or trade organizations provide specialized evaluation manuals, materials guides, and recommended techniques for a variety of pavement maladies, there has been a tendency of these groups to inadequately address the bridging of engineering evaluation to practical maintenance or rehabilitation strategy and application. The bridging process usually works well after a failure has occurred and there is a need for a full scale investigative, design, and specification effort; however, for the routine, daily interaction of the pavement system and its need for continuing attention and preventive maintenance, reliance is still placed on local individuals doing their best with local solutions, correctly or incorrectly applied.

Summary

In summary, the methods of detecting, classifying and repairing pavement system failures require using proper techniques, materials, and implementation of an economic feasibility study. The key to solving pavement system failures is the establishment and use of an ongoing method of repetitive repair processes integrated into a long-term maintenance and management strategy. Though the desired condition is to prevent being placed in the position of needing failure analysis by extensive front end planning and design, following good construction practices and controls, and developing and utilizing an active pavement management program, some failure is inevitable.

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Contributing Reviewers

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