Quantifying Pavement Sustainability in Project and Network Level Perspectives

Peter Chan, M.ASc Candidate
University of Waterloo Department of Civil and Environmental Engineering
200 University Avenue W., Waterloo, ON, N2L 3G1

Dr. Susan L. Tighe, Ph.D, P.Eng, Professor, Canada Research Chair
University of Waterloo Department of Civil and Environmental Engineering
200 University Avenue W., Waterloo, ON, N2L 3G1

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ABSTRACT
The general objective of the paper is to summarize some of the key findings from a study that the Centre for Pavement and Transportation Technology at the University of Waterloo has with the Ministry of Transportation of Ontario (MTO). The main goal of the study is to develop a practical framework to quantify sustainable pavement engineering practices that are currently portrayed in Ontario highway projects. Both network and project level applications are considered in this framework. In essence, the paper explores how sustainability can influence in the project decision making or in maintenance and rehabilitation planning activities. The basis of the quantification is the three fundamental grounds of sustainability: economic, society, and environment. The assessment of sustainability would involve primarily examining life cycle cost, green pavement rating scores, and pavement service life of an alternative. This paper will explore the development of the pavement sustainability quantification and also how the quantification connects to the daily practices by the Ministry of Transportation of Ontario. In short, quantifying pavement sustainability is a complementary activity to MTO daily pavement engineering work. Therefore, such quantification should be simple to understand and flexible, yet reflect the sustainable elements of an alternative in a fair and sensitive manner.

Project Background and Introduction

Roadway infrastructure is critical component that dictated development of society. The pavement structure of the road ages, and deteriorates over time. Proper construction and maintenance activities are essential to ensure roads provide the required performance for users. In the society today where resources and funding are limited, transportation agencies have begun seeking ways to utilize the resources to maximize benefits as part of the daily operation. In general, sustainability is about maintaining the current infrastructure without compromising the need or resources of the future generation. Three elements form the basis for sustainability: economy, society, and environment. Sustainable pavement is about integrating these three basic elements into pavement engineering practices. Currently, there is no standard mechanism that quantifies sustainability in a simple and balance manner.

With the concept of sustainability wide spreading in the general public, the need of quantifying sustainable practices is highly regarded. The initiatives by LEED™, Greenroads, and GreenLITES certification programs are leading examples of interest in quantifying sustainable practices. The Ministry of Transportation (MTO) owns over 10,000 kilometres of highways in the province of Ontario is currently working on a project called “Quantifying Pavement Sustainability” under its Highway Infrastructure Innovation Funding Program. This project is a joint effort by the University of Waterloo, Centre of Pavement and Transportation Technology (UW CPATT) and MTO. The ultimate goal of the project is to develop a framework for MTO to practice sustainable pavement.

In this project, different sustainable pavement practices are reviewed through literature review and CPATT/MTO sustainable pavement workshop. The goal of the literature review is to understand different pavement technologies and materials available through research papers, MTO specifications, and project reports from various parties. The literature review attempts to capture the state-of-practice of sustainable pavement materials, designs, constructions, maintenances and rehabilitations. CPATT/MTO sustainable pavement workshop is a gathering of pavement professionals in Ontario. The workshop discusses the current state of sustainable pavement practices in Ontario and implementing sustainable pavement in the future. An analysis was conducted to determine the typical economic and environmental savings between different pavement construction and rehabilitation methods. The analysis result was used as supplemental data for the development of a green pavement rating system for MTO.

This framework in this project should encompass all aspects of pavement engineering practice at project level and network level, with the integration of sustainability as a decision support criteria. The framework considers sustainability through two elements: quantification and indicator. The quantification of sustainability attempts to capture the sustainable element portrayed in the practice. The quantification of sustainability involves with green pavement evaluation, life cycle cost (LCC) computation, and pavement service lives comparison. The ultimate goal of the quantification is to prepare the data necessary to compute sustainability indicators. Indicators are developed in this project to measure the extent of sustainability portrayed by a design alternative. Hence, the indicators discuss in this paper act as decision support tool for MTO practice. These indicators are numerical values calculated from the data obtained from the quantification. Indicator is a simple way to represent pavement sustainability. The main emphasis of this paper is in the quantification and indicator aspects of this sustainable pavement framework. In order to quantify pavement sustainability, the first step is to understand the basis and tools used in the quantification process.

Basis for Quantification

This section describes the basic information or grounds required to quantify pavement sustainability. Due to the difference in project level and network level work, two distinct mechanisms are developed to provide a fair quantification of project and network level activities in the project. Hence, different indicators are developed in this project to assess pavement sustainability.

The Life Cycle Cost (LCC) of the pavement provides an economic assessment of a pavement alternative. Life cycle cost of a pavement is typically the summation of initial construction cost, maintenance cost, and operating cost subtracted the salvage value of pavement over a programming period discounted in present worth value. At project level, MTO allows consultant to compute life cycle cost through deterministic or probabilistic Life Cycle Cost Analysis (LCCA) based on project size (Lane, 2005). The deterministic LCCA in MTO is calculated as present worth as shown in equation 1 and 2.

$$PW_{TOT} = \left[\sum\left(C \times \left(\frac{1}{1+i}\right)^{n}\right)\right] - SV_{PW} \tag{1}$$

$$SV_{PV} = \left(\frac{L_{REM}}{L_{EXP}}\right) \times C \times \left(\frac{1}{1+i}\right)^{m} \tag{2}$$

Where:

PW_{TOT}	= Total Present Worth
SV_{PW}	= Salvage Value in Present Worth
m	= Analysis Period
n	= n^{th} Year of Implementation
L_{EXP}	= Expected Service Life
L_{REM}	= Remaining Service Life = L_{EXP} – (m – n)
C	= Cost of Rehabilitation/Construction
i	= Discount Rate 5.3%

The probabilistic LCCA involves the probability distributions and simulations through statistical software to compute the life cycle cost of the project. The probabilistic LCCA is not considered in the economic analysis component in this project

At network level, MTO obtains life cycle cost estimation through their pavement management system, PMS2. Intuitively, the lower the LCC suggest a more economically feasible alternative.

With the initiatives of LEED™ and Greenroads, MTO is currently developing a Green Pavement Rating System (GPRS) in conjunction with this project. This Green Pavement Rating System is designed to evaluate the environmental aspect of pavement alternatives at project level in Ontario. This GPRS primary focus in four major themes of the environment (Chan, 2009):

- Pavement Technology (PT) – Maximum 9 credits
- Material and Resources (MR) – Maximum 14 credits
- Energy and Atmosphere (EA) – Maximum 9 credits
- Innovation and Design Process (ID) – Maximum 4 credits

The MTO GPRS consists a total of maximum of 36 credits. The amount of credits scored by a pavement alternative dictates its environmental friendliness. There are currently four certification levels suggested by the MTO GPRS (Chan, 2009):

- Trillium – Minimum 20 credits
- Gold – Minimum 15 credits
- Silver – Minimum 11 credits
- Bronze – Minimum 7 credits

The amount of credits scored by a pavement alternative dictates its environmental sustainability. For this project, the MTO GPRS serves as the platform to evaluate the environmental aspect of sustainability. Further content about the MTO GPRS is not discussed this paper. This project uses MTO GPRS as a platform for environmental quantification for pavement alternatives.

In the social perspective of sustainability, pavement service life is treated as a social consideration of sustainability for the indicator computation. Pavement service life is typically considered in years by transportation agencies. The service life of a pavement is the period of time from construction completion until the pavement condition is considered to be unacceptable, that rehabilitation or replacement is required to restore serviceability (Lane, 2005). Pavement service lives can be influence by a few factors such as:

1. Nature of the technology (such as in-place recycling versus mill and overlay).
2. Climatic factor of the region, same treatment could perform differently due to different local climate conditions.
3. Agency and contractor experiences associated with the technology.
4. Research effort and modeling associated with the technology.

Due to the predictive nature of pavement service life, it is not appropriate to conclude a specific service life for project level design alternatives. At the project level, a decision is made based on the pavement design suggested by the consultants. Hence, it is difficult to predict the service life of a design that is proposed by a consultant. However at network level, the maintenance and rehabilitation programming involves preparing the required budget to perform the necessary maintenance and rehabilitation treatment to ensure adequate performance over the life of the pavement. In MTO, the service lives of pavement treatment are found in MTO pavement management system, PMS2.

Project Level Sustainability Indicator: Green Discounted Life Cycle Cost (GDLCC)

Given the environmental and economic information, a simple way to measure sustainability is by performance indicator. The Green Discounted Life Cycle Cost (GDLCC) is the first sustainability indicator developed for this project. GDLCC considers the LCC and GPRS credits of an alternative. The computation equation for GDLCC is shown in equation 3.

$$GDLCC = LCC \times \left(1 - \left(0.2 \times \frac{GPRS}{36}\right)\right) \tag{3}$$

Where:
GDLCC = Green Discounted Life Cycle Cost
LCC = Life Cycle Cost of Alternative
GPRS = Green Pavement Rating Credits

MTO originally suggested equation 3 to compute GDLCC as a preliminary indicator to measure sustainability. Equation 3 suggests that GDLCC is a discounted life cycle cost of an alternative. The amount of discount that an alternative can achieve is directly proportional to the amount of GPRS credits scored on the alternative. The constant of 0.2 in equation 3 is suggested by MTO as a factor that controls the sensitivity of GDLCC. GDLCC demonstrates the economic aspect of sustainability by considering LCC of an alternative; and the environmental aspect of sustainability by considers the GPRS credits of an alternative. The lower the GDLCC of an alternative, the more sustainable the pavement practice.

The weakness of equation 3 is the low sensitivity of GDLCC suggested by the constant 0.2. For example, if a project has two alternatives where alternative 1 costs 80% of alternative 2 in LCC, then the GPRS credits of these two alternatives become irrelevant to make an impact in the GDLCC calculation because the cheaper alternative will always produce a smaller GDLCC from equation 8. Hence, it is possible a pavement project having design alternatives with a LCC difference of 20% or more. Therefore, equation 3 requires modification to improve sensitivity of the alternative.

The modified GDLCC equation is shown in equation 4 as GDLCC Type P, where Type P represents a project level indicator.

$$GDLCC\ Type\ P = LCC \times \left(1 - \left(\frac{Min(10, MR)}{10} \times \frac{GPRS}{36}\right)\right) \tag{4}$$

Where:
MR = Material and Resource Credits in MTO GPRS

In equation 4, the 0.2 shown in equation 3 is removed and a 10% of Material and Resources (MR) credit is replaced. MR is a subset of MTO GPRS credits. There are 14 total credits in the MR category of MTO GPRS as suggested previously. Intuitively, an environmental friendly pavement design alternative should achieve a high GPRS score in the evaluation with an excellent utilization of recycled and reused material. As a result, an alternative that scores a high GPRS credits should represent a high MR credits. Therefore, an alternative that scored high GPRS credits should yield a lower GDLCC using equation 4 than equation 3. Figure 1 shows the savings difference based between equation 3 and equation 4. Figure 1 considers the percent savings between equation 3 and 2 using 33 MTO GPRS evaluations and LCC. It is evident that GDLCC computed by equation 4 provides a greater degree environment emphasis than equation 3.

Project Level Sustainability Indicator: Parameter D

Parameter D is an indicator developed by the CPATT research team to measure pavement sustainability at the project level. It also utilizes LCC and GPRS credits of an alternative. D is developed primarily to address the weak sensitivity of GDLCC as shown in equation 3 in the early stage of MTO GPRS evaluation trials. The ultimate goal of D is essentially the same as GDLCC: to provide a simple and sensitive way to compute pavement sustainability at project level for MTO.

D is developed using through the Pythagorean Theorem as shown in equation 5. Parameter D is initially calculated from transforming GPRS credit and LCC into x and y Cartesian coordinates using equation 6 and 5 respectively.

$$D = \sqrt{x^2 + y^2} \tag{5}$$

$$x = 1 - \left(\frac{GPRS}{36}\right) \tag{6}$$

$$y = \left(\frac{alt\ LCC}{Max(alt\ LCC)}\right) \tag{7}$$

Where:
Alt LCC = LCC of an alternative in a project
Max(alt LCC) = Most expensive LCC alternative available in a project

Equation 6 and 5 are developed LCC and GPRS trial data provided by MTO. Equation 6 and 5 convert GPRS score and LCC into fractions range from 0 to 1. Equation 6 suggests that the smaller value of x is calculated from a higher GPRS score. On the other hand, equation 7 represents the quotient of an alternative's LCC and the most expensive alternative's LCC available in the project. Equation 7 suggests that the smaller value of y is resulted from lower LCC in a project alternative. The most sustainable alternative should have a small D value.

The initial parameter D calculation using equation 5 and 4 are not sensitive to distinguish sustainable practices. Therefore, these two equations are modified for improve sensitivity. Equation 8 and 7 are the revised to better reflect the sensitivity of x and y.

$$x = 1 - \left(\frac{Min(GPRS, 20)}{20}\right) \tag{8}$$

$$y = \left(\frac{alt\ LCC}{Max(alt\ LCC)}\right)^4 \tag{9}$$

Equation 8 suggests if a project alternative scores 20 GPRS credits or more (trillium certification), the x value becomes 0. The value 20 is selected as the denominator because it is impossible to score all 36 GPRS credit by a project alternative. On the other hand, equation 9 raises the exponent of equation 7 by 4. The exponent raise in equation 9 produces a more sensitive effect on LCC differences than equation 7. Figure 2 shows the graphical representation of D with four representative alternatives with total of eight D vectors using equation 5 to 7. Table 1 shows the corresponding values of the vectors from Figure 2.

From Figure 2, it is evident that the dashed vectors are better at demonstrating the economic and environmental relationship between the four chosen alternatives as they distribute among different regions on the figure and the length of the vector can be easily distinguishable. Based on the revised case results in Figure 2 and Table 1, mill and overlay (Alt. 4) provides the shortest dashed vector length, and cold in-place recycling (Alt. 12) comes closely for second shortest dashed vector length in this example. It is concluded for this example mill and overlay is the most sustainable alternative available, though it is not the most environment friendly alternative in this example.

Difference between GDLCC and Parameter D

Both GDLCC Type P and parameter D attempt to provide a simple measure of pavement sustainability for a project alternative. GDLCC Type P and parameter D work by using mathematics to correlate economic and environmental aspects of a pavement design alternative. User should understand the most sustainable alternative suggested by the indicator might not represent the most environmental friendly alternative. The economic aspect of sustainability is highly regarded in sustainable practices as well. Users should also aware the differences between GDLCC Type P and parameter D when calculating these indicators. The advantages of GDLCC Type P include:

- Simple arithmetic computation allows for easy changes of the equation to improve sensitivity of results or programmed into software.
- Results are comparable to LCC of the project.
- The sensitivity can be adjusted by utilizing GPRS and MR scores simultaneously
- GDLCC Type P results are comparable within the same project only.

The advantages of parameter D include:

- It provides a balanced approach for comparing economic and environmental aspects of an alternative simultaneously.
- It involves different computation compared to GDLCC, yet it is still simple to program into the computer software.
- It is a standalone indicator, not a representation of cost.
- The potential to develop thresholds between sustainable and not sustainable alternatives is possible as more GPRS evaluations are completed.
- A graphical representation is a good way to observe the sustainability of the alternatives available.

- It is capable to assess design alternatives within different projects in a given highway network

Network Level: PMS2 and GDLCC Type N

Network level pavement engineering involves need analysis, budget scheduling, performance forecasting, maintenance and rehabilitation (M&R) analysis. MTO uses pavement management system, PMS2, as a central database that perform network level pavement engineering at daily basis. For this project, sustainable network level practice is examined through maintenance and rehabilitation analysis. Maintenance and rehabilitation analysis involve finding the proper maintenance or rehabilitation treatments over the life cycle of pavement under specific constraints. These constraints can be available budget, pavement condition index (PCI) thresholds, analysis method, discount rate, and programming period. M&R analysis aims to determine the pavement rehabilitation treatment that provides optimal pavement performance at the lowest cost.

PMS2 generates M&R analysis for highway sections based on the highway data. Table 2 shows the relevant output for PMS2 for the computation of sustainable pavement indicator at network level. For this project, the indicator for network level is Green Discounted Life Cycle Cost Type N, with N to denote as a network level indicator. GDLCC Type N is a modified indicator based on GDLCC for using at network level pavement management. GDLCC Type N assesses different alternatives generated by PMS2. Equation 30 is a modification of equation 4 to compute GDLCC Type N.

$$GDLCC\ Type\ N = \left[LCC \times (A/P\,, i, PCI_{MIN})\right] \times \left[1 - \left(\frac{Min(MR, 10)}{10}\right) \times \left(\frac{GPRS}{36}\right)\right] \quad (10)$$

Where:

LCC	= Implementation cost of treatment proposed by PMS2 in present worth
(A/P, i, PCI_{min})	= Factor to convert present worth to equivalent annual worth, as per equation 11 (Fraser et al., 2000)

$$(A/P\,, i, PCI_{MIN}) = \frac{i(1+i)^{PCI_{MIN}}}{(1+i)^{PCI_{MIN}} - 1} \quad (11)$$

i	= Discount rate
PCI_{min}	= Minimum service life based on PCI as suggested by PMS2 (dependent on treatment)
GPRS	= Typical total GPRS credits for a specific treatment
MR	= Typical Material and Resources Credits from MTO GPRS for a specific treatment

Equation 30 suggests GDLCC Type N considers the economic aspect of sustainability by maintaining the final GDLCC value as a cost. However, at the network level, equivalent annual worth is used to express GDLCC Type N instead of present worth. PMS2 M&R analysis result provides the LCC estimate in terms of present worth. The discount rate for conducting M&R analysis and GDLCC Type N computation should equal to ensure consistency.

The conversion of GDLCC into equivalent annual worth as shown in equation 30 relates to the social aspect of sustainability. The presentation of GDLCC as equivalent annual worth rather than present worth allows comparison across different pavement treatments with different service lives. PMS2 contains performance models for different pavement treatments to predict PCI values over pavement life cycle. The typical minimum service lives for rehabilitation is chosen to allow more proactive planning and conservative GDLCC Type N calculation. At project level, it is not appropriate to apply a minimum PCI service life as a social cost discount because matching consultants' pavement design with the models available in PMS2 is unrealistic.

Again, equation 30 considers GPRS credits and MR credits. At network level, the typical GPRS credits and MR credits for a treatment are applied to equation 30. Currently, these typical values are averages estimated from project level GPRS evaluations completed by MTO. Table 3 shows the current typical GPRS and MR credits calculated. The values from Table 3 are averages from MTO project level GPRS evaluations in 2009.

Table 4 shows an example PMS2 M&R Analysis output data for GDLCC Type N calculation of three alternatives: full depth reclamation, mill and overlay, and cold in-place recycling. Table 5 shows the GDLCC Type N calculation results using equation 31. Based on the results in Table 5, cold in-place recycling shows the lowest GDLCC Type N. Hence, it is the most sustainable treatment in this example. As more MTO GPRS evaluations will be completed in 2010, the typical values shown in Table 3 can be revised to represent different rehabilitation treatments in Ontario with better accuracy.

Conclusions

This paper explores the quantification of pavement sustainability and three sustainable pavement indicators: GDLCC Type P, Parameter D, and GDLCC Type N. These three indicators evaluate pavement sustainability in economic, social, and environmental perspectives. Although the indicators for this paper are proposed for MTO practice, the basic premises for pavement sustainability quantification are credits from Green Pavement Rating System (or any kind of environmental quantification), pavement service lives, and life cycle cost of an alternative. The paper also discusses the difference between the indicators. Nevertheless, the ultimate goal of these indicators are to provide a simple mean to quantify pavement sustainability for MTO staff in daily project level and network level practices.

Future Directions

It is expected more data in 2010 will aid in further modify indicator equation in a more sensitive manner to quantify sustainable pavement practices. More detail guidelines will be developed to demonstrate the use of the proposed indicators. Case studies with real MTO project data and PMS2 results are also examined in the future to help putting the indicator into MTO daily work routine. The integration of using green pavement rating system in MTO daily routine provides a mechanism to quantify pavement sustainability.

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Tables

Table 1: Parameter D Results for Figure 2

	Vector Name (Treatment Alternative)	**X (Equation 6)**	**Y (Equation 7)**	**D (Equation 5)**
Original Case	Alt. 1 – New AC	0.92	0.85	1.25
	Alt. 4 – M&O	0.86	0.79	1.17
	Alt. 5 – FDR	0.75	0.93	1.20
	Alt. 12 – CIR	0.64	0.95	1.14
		X (Equation 8)	**Y (Equation 9)**	**D (Equation 5)**
Revised Case	(REV) Alt. 1 – New AC	0.85	0.52	1.00
	(REV) Alt. 4 – M&O	0.75	0.39	0.85
	(REV) Alt. 5 – FDR	0.55	0.79	0.96
	(REV) Alt. 12 – CIR	0.35	0.80	0.87

Where:

Alt. = Alternative
New AC = New Asphalt Construction
M&O = Mill and Overlay
FDR = Full Depth Reclamation
CIR = Cold In-place Recycling

Table 2: PMS2 Output

PMS2 Output	**Example / Description**
Location Information	Highway Identification, direction, stationing, starting and ending location
Need Year	The year highway need rehabilitation
Implementation Year	The year a rehabilitation is implement on the section
Treatment	Treatment being done on a highway (such as mill and overlay, cold in-place recycling)
Implementation Cost	Cost to implement the suggested treatment expressed in present worth
Effectiveness	Area of PCI versus time plot, a measure of pavement performance
Effectiveness Factor	A factor that correlate to annual average daily traffic of the highway
Cost Effectiveness	The quotient between effectiveness and cost

Table 3: Typical GPRS Credits and MR Credits for GDLCC Type N

Treatment	Average Assumed at Network Level	
	GPRS Credits	**MR Credits**
Mill and Overlay	6.11	4.41
Full Depth Reclamation or In-Place Processing	12.44	7.44
Expanded Asphalt Stabilization	14.8	8.46
Cold In-Place Recycling (Cold In-Place Recycling with Expanded Asphalt)	14	8
New Asphalt Reconstruction	3	2
Overlay	5.5	4.5
Rubblization and Overlay	9	5.6
New Concrete Reconstruction	6	2

Table 4: Example of GDLCC Type N Computation Data

Alt. #	From PMS2					GPRS (TYP.)[1]	MR (TYP.)[1]
	Description	**Need Year**	**Imp. Year**	**Imp. Cost**	**PCI_{min}**		
1	FDR+HM Overlay3F	2013	2013	$3,990,782	13	12.44	7.44
2	Mill+HM Overlay2 FWY	2013	2013	$2,645,575	10	6.11	4.41
3	CIR+HM Overlay 2F	2013	2013	$3,176,540	12	14	8

Where:
[1]From Table 3
Alt. # = Alternative Number
Imp. Year = Implementation Year
Imp. Cost = Implementation Cost
FDR+HM Overlay3F = Full Depth Reclamation with 3 Lifts Overlay Freeway Option
Mill+HM Overlay2FWY = Mill and Overlay 2 Lifts Freeway Option
CIR+HM Overlay2F = Cold In-place Recycling with 2 Lifts Overlay Freeway Option

Table 5: GDLCC Type N Computation Results

Alt. #	Description	$(A/P,i, PCI_{min})$	GDLCC Type N
1	FDR + HM Overlay 3F	0.1064	$315,452
2	Mill + HM Overlay 2F	0.1295	$316,959
3	CIR + HM Overlay 2F	0.1128	$246,838

Where:
$(A/P,i, PCI_{min})$ = Conversion factor to convert present worth to equivalent annual worth

Figures

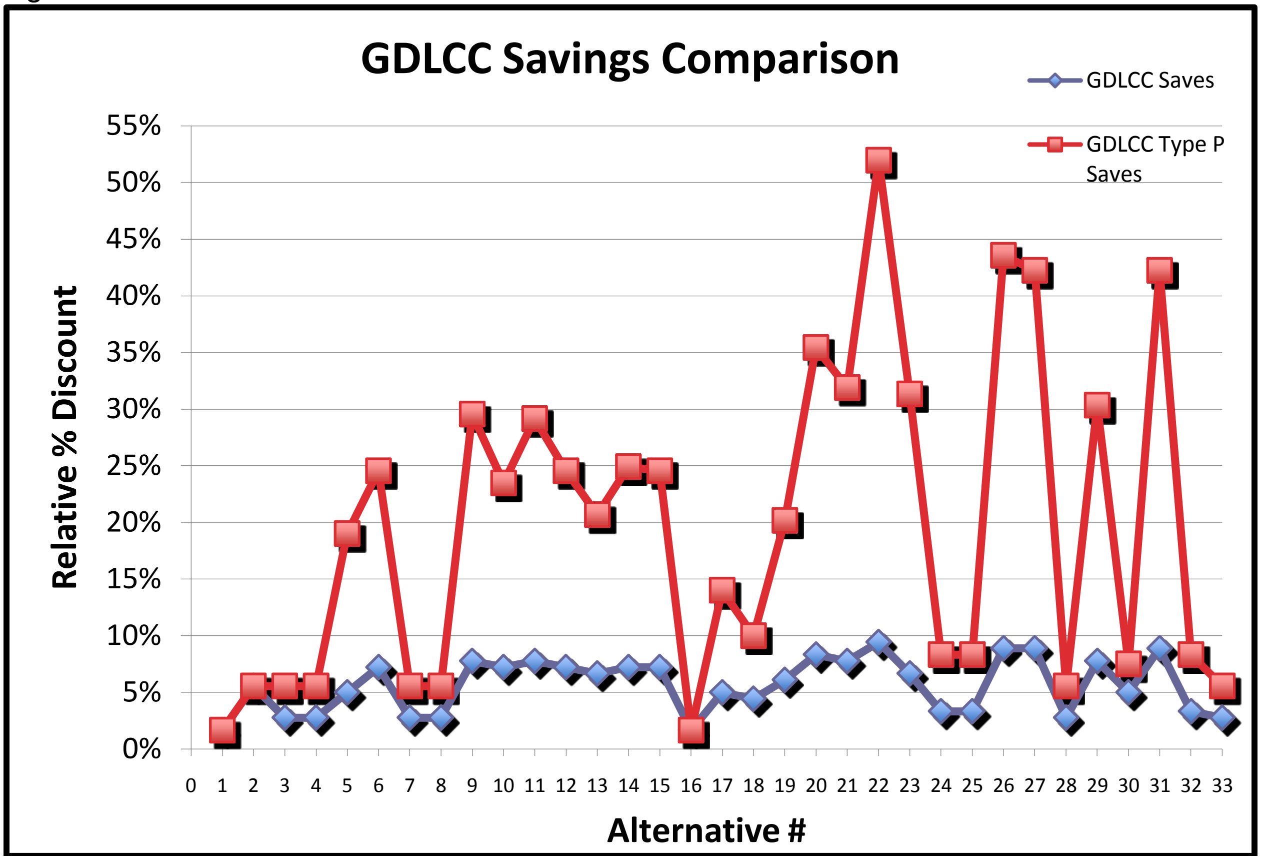

Figure 1: GDLCC Savings Comparison

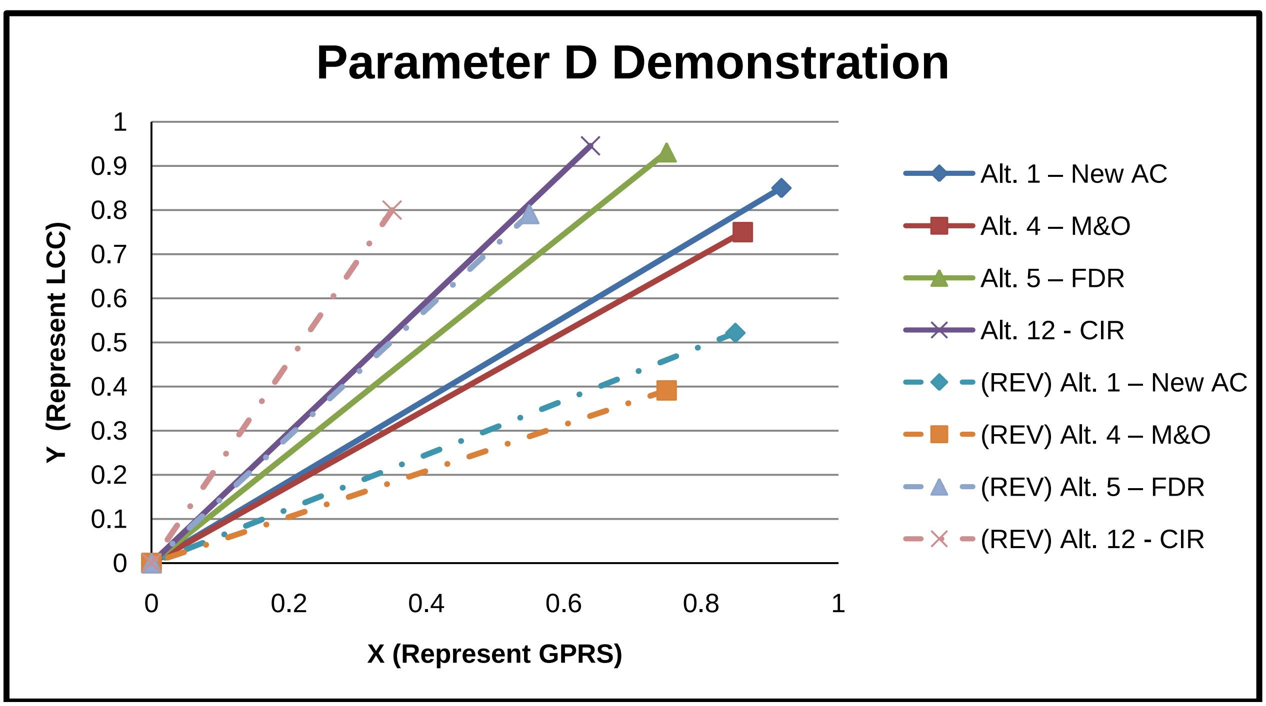

Figure 2: Parameter D Demonstration