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Maintenance Activities**

Shadi B. Anani and Samer M. Madanat
University of California, Berkeley
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Shadi B. Anani, P.E.¹ and Samer M. Madanat, M.ASCE²

Abstract: This paper focuses on the estimation of highway maintenance marginal costs. Highway maintenance marginal cost has been estimated in the literature using the perpetual overlay indirect approach. This approach assumes that pavement overlay costs dominate maintenance costs and ignores other maintenance activities. This paper focuses on two questions. First, is it acceptable to ignore the less costly activities? Second, if multiple maintenance activities are to be considered, is it acceptable to ignore their interdependence? The results show that less costly maintenance activities cannot be ignored. Furthermore, if multiple activities are to be considered, their interdependence should be taken into account.

Keywords: Marginal cost; Highway maintenance; Realistic strategy; Multiple activities

Introduction

A typical highway agency uses multiple types of highway pavement Maintenance, Rehabilitation and Reconstruction (MR&R) activities. Often, highway agencies have MR&R strategies that are *condition-responsive*; in other words, a given MR&R activity is performed each time a given

¹ (Corresponding author). Dept. of Civil and Environmental Engineering, Institute of Transportation Studies, University of California, Berkeley, 109 McLaughlin Hall #1720, Berkeley, CA 94720-1720. E-mail: shadianani@gmail.com

² Professor, Dept. of Civil and Environmental Engineering, Institute of Transportation Studies, University of California, Berkeley, 109 McLaughlin Hall #1720, Berkeley, CA 94720-1720. E-mail: madanat@ce.berkeley.edu

measure of pavement condition reaches a predetermined trigger level. Each type of activity can be triggered by a different type of pavement condition, such as rutting, alligator cracking or roughness. As a result of such a condition-responsive strategy, an increase in traffic loading leads to an (indirect) increase in the MR&R total cost incurred by the highway agency. An increase in traffic loading accelerates pavement deterioration, which brings forward all future MR&R activities which, in turn, increases their present value.

The increase in the MR&R total cost resulting from an additional unit of traffic loading (e.g. an additional ESAL) is the *MR&R marginal cost*. This is only one component of the marginal social cost. Other components of the marginal social cost include the private marginal cost (the increase in own vehicle operating cost), and the highway user marginal cost (the increase in the cost of subsequent vehicles as a result of worse pavement condition). This paper only focuses on the MR&R marginal cost component.

From an equity and economic efficiency point of view, it is desirable that each vehicle pay its marginal social cost. There is growing interest for implementing marginal cost pricing, which is a pricing strategy that sets price equal to the marginal social cost, one component of which is MR&R marginal cost. The lack of accurate estimates of MR&R marginal cost remains an important obstacle to such implementation. Much of this inaccuracy stems from unrealistic simplifying assumptions, such as the assumption that the only MR&R activity used by a highway agency is an overlay of constant intensity.

Bruzelius (2004) surveys the different approaches used in the literature to estimate MR&R marginal cost. Among these approaches, the *perpetual overlay indirect approach* is the most detailed because it explicitly models the steps that take place between the increase in traffic loading and the increase in MR&R cost. Bruzelius (2004) refers to it as the “indirect approach”.

This approach assumes that pavement overlay (resurfacing) costs dominate MR&R costs, and it ignores all other MR&R costs. It uses an infinite analysis horizon and assumes that a pavement is overlaid as soon it deteriorates to a predetermined trigger level (Newbery 1988; Small et al. 1989). It first relates changes in traffic loading (additional ESAL) to changes in overlay frequency (an additional ESAL brings forward the future overlays), and possibly changes in the overlay intensity (thicker overlays in anticipation of higher traffic loadings in the future). Then, it relates these changes in overlay frequency (and intensity) to MR&R marginal cost.

Following Small et al. (1989), Vitaliano and Held (1990) and Lindberg (2002), an additional ESAL is defined as an event that recurs annually, and the MR&R marginal cost is defined as the change in the annualized cost of future overlays, as a result of increasing the traffic loading by 1 ESAL this year and every year in the future³. This is referred to as the *recurring additional ESAL*.

The perpetual overlay indirect approach includes studies by Newbery (1988), Small et al. (1989), Vitaliano and Held (1990), Transportation Research Board (1996), Lindberg (2002) and Haraldsson (2007a). The basic formulation in the state-of-the-art proceeds as follows. Consider one lane of a flexible pavement section of a highway. Let constant L , such that $L > 0$, be the annual traffic loading for this section (ESAL/year). Also, consider a highway agency that uses a simple MR&R strategy with only one type of MR&R activity, namely an overlay of constant intensity that is triggered by a specific pavement performance measure, M . The pavement section receives an overlay each time M reaches trigger level M_f . Assume that pavement deterioration and improvement are deterministic. Let X , such that $X > 0$, be the number of ESALs to failure for

³ After the increase, all years have the same annual traffic loading, which exceeds the current annual traffic loading by one.

this pavement section. Let T (year) be the overlay life, i.e. the time between two consecutive overlays.

$$T = \frac{X}{L} \quad (1)$$

Although Equation (1) is derived for the case of one lane, it can also be applied to the case of a highway section with multiple lanes, provided that all lanes are only overlaid at the same time, in which case these lanes can be treated as a system of lanes. When Equation (1) is used for a system, X and L should include the combined number of ESALs for all lanes. The exact definition of failure for this system depends on the highway agency (for example, the agency might overlay the system each time any lane fails), and it will affect the value of X .

Some studies take weathering (or aging) into account (Newbery 1988; Small et al. 1989; Vitaliano and Held 1990). Weathering is the additional deterioration resulting from the passage of time and the climate. However, we show the basic formulation used by previous studies.

Under constant annual traffic loading L , the values of X and T depend on the underlying pavement structure, the climate and the value of the trigger level (M_f). These three factors are held constant.

Let U be the unit cost (\$/mile) for an overlay. The value of U should be consistent with the values of X and L ; for example, if X and L are defined for a system of lanes, then U should be the unit cost for overlaying all lanes. Fig. 1 shows the cash flow diagram for all future overlays. Present time is time 0.

Let r , such that $r > 0$, be the discount rate per annum. Let V be the present value of all future overlays (\$/mile). Using continuous discounting:

$$V = U \cdot \sum_{j=1}^{\infty} \exp(-r \cdot T \cdot j) = U \cdot \sum_{j=1}^{\infty} (\exp(-r \cdot T))^j = U \cdot \frac{\exp(-r \cdot T)}{1 - \exp(-r \cdot T)} \quad (2)$$

The third equality in Equation (2) comes from the assumption that $(-r \cdot T)$ is strictly negative and finite. As a result of this assumption, $0 < \exp(-r \cdot T) < 1$. Therefore, the infinite geometric series converges. Equation (2) can be written as:

$$V = \frac{U}{\exp(r \cdot T) - 1} \quad (3)$$

Using continuous discounting⁴, the annualized cost of all future MR&R activities equals $(e^r - 1) \cdot V$. The additional ESAL is defined as a recurring additional ESAL (Lindberg 2002; Small et al. 1989; Vitaliano and Held 1990). Equation (4) gives the definition of C'_{simple} , the MR&R marginal cost (\$/ESAL/mile) resulting from the MR&R strategy that uses only one type of activity:

$$C'_{simple} := \frac{d((e^r - 1)V)}{dL} = (e^r - 1) \cdot \frac{dV}{dT} \cdot \frac{dT}{dL} \quad (4)$$

This expression for MR&R marginal cost implicitly assumes that the increase in traffic loading (at time 0) takes place immediately following an MR&R activity. This is clear from Fig. 1 and Equation (2). This assumption is acceptable for comparative analysis.

Using Equation (3):

$$\frac{dV}{dT} = -r \cdot U \cdot \frac{\exp(r \cdot T)}{(\exp(r \cdot T) - 1)^2} \quad (5)$$

Using Equation (1):

⁴ We use continuous discounting for annualizing V in order to be consistent with its use for expressing V . Note that this approach diverges from some studies that have used a mixture of continuous discounting (for expressing V) and annual discounting (for annualizing V , i.e. $r \cdot V$) (Lindberg, 2002; Small et al., 1989; Vitaliano and Held, 1990).

$$\frac{dT}{dL} = \frac{-X}{L^2} = \frac{-T}{L} \quad (6)$$

Then, using Equations (4), (5) and (6):

$$C'_{simple} = \frac{(e^r - 1)r.U.T.\exp(r.T)}{L.(\exp(r.T) - 1)^2}, \text{ where } T=X/L \quad (7)$$

Equation (7) is essentially a simplified version of Small et al.'s equation (1989, equation 2-9b with $m=0$) and Vitaliano and Held (1990, equation 8, with $\theta=1$ or $m=0$), when the effect of weathering, which is included in these works, is ignored.

Recent research has shown that a strategy in which a pavement receives an overlay of constant intensity every time its condition deteriorates to a constant, predetermined trigger level is optimal among strategies for which a single activity is used, for both the finite horizon problem (Ouyang and Madanat 2006) and the infinite horizon problem (Li and Madanat 2002). Still, the assumption made by the perpetual overlay indirect approach that the only MR&R activity used by a highway agency is an overlay of constant intensity is questionable. In reality, a highway agency uses different types of MR&R activities, such as pothole repairs, patching, sealing, thin overlays, regular overlays and reconstruction; and it uses different triggers for different activities. Since each highway agency has its own MR&R strategy, it is important to take into account this strategy when determining MR&R marginal cost.

It should be noted that some studies have estimated MR&R marginal cost under multiple types of MR&R activities, but they have used approaches other than the perpetual overlay indirect approach. For example, Li et al. (2001), Link (2002) and Haraldsson (2007b) use the econometric approach. In the econometric approach, a pavement MR&R total cost function is estimated using econometric techniques, and then the pavement MR&R marginal cost is determined from this total cost function. The MR&R total cost function includes independent

variables such as traffic, road geometry, pavement structure and climate. The econometric approach does not explicitly model MR&R strategies used by a highway agency.

This paper improves the estimation of MR&R marginal cost (using the perpetual overlay indirect approach) by relaxing the assumption that a highway agency uses only one type of MR&R activity. It presents a methodology to estimate MR&R marginal cost taking into account the pavement management strategies used in practice. The paper asks two questions. First, is it acceptable to ignore the less costly MR&R activities? Second, if multiple MR&R activities are to be considered, is it acceptable to ignore their interdependence? In order to answer these questions in an intuitive way, this study makes some simplifying assumptions of its own. For example, as the next section explains, only two activities are considered, and specific pavement deterioration models and pavement condition trigger levels are replaced by the number of ESALs to failure.

Methodology

Consider one lane of a flexible pavement section of a roadway. Flexible pavements undergo both rutting and cracking. Also, consider a highway agency that uses an MR&R strategy with two activities C and R, which are triggered by cracking and rutting, respectively. Activity C is performed each time alligator cracking reaches trigger level C_f (percent), and it consists of patching. Activity R is performed each time rutting reaches trigger level R_f (mm), and it consists of leveling and overlaying. The interdependence between the two activities will be taken into account. Assume that activity C improves cracking but has negligible effect on rutting; however, activity R improves both rutting and cracking. Assume that pavement deterioration and improvement are deterministic.

Assume that ESAL is the appropriate deterioration equivalence factor for both activity types C and R. Let constant L, such that L>0, be the annual traffic loading (ESAL/year). Let X_C and X_R , both strictly positive, denote the number of ESALs to failure for activities C and R, respectively, for a given pavement section. The values of X_C and X_R depend on pavement structure, the climate and the values of the trigger levels (C_f and R_f). Assume that activity C is performed more frequently than activity R, i.e. $X_C < X_R$. Let T_C (year) be the time between two consecutive type-C activities that do not have a type-R activity between them:

$$T_C = \frac{X_C}{L} \quad (8)$$

Let T_R (year) be the time between any two consecutive type-R activities:

$$T_R = \frac{X_R}{L} \quad (9)$$

We ignore the effect of weathering, so X_C and X_R are independent of L. To account for weathering, we would have to use specific deterioration models⁵. By keeping the methodology general and simple, it is easier to gain intuition about the effect of including multiple activities.

Let n be the number of times type-C activity is performed between any two consecutive type-R activities. It is an integer, so floor division is used in Equation (10).

$$n = \left\lfloor \frac{T_R}{T_C} \right\rfloor = \left\lfloor \frac{X_R/L}{X_C/L} \right\rfloor = \left\lfloor \frac{X_R}{X_C} \right\rfloor \quad (10)$$

⁵ In order to take weathering into account, Small et al. (1989) use a particular deterioration model, and they derive the following for one type of MR&R activity: $T = X_0 \cdot \exp(-m \cdot T) / L$, where m is an environmental coefficient (they use $m=0.04$), and X_0 is the number of ESALs to failure under conditions of negligible weathering (i.e., when $L \rightarrow \infty$, so $T \rightarrow 0$). The actual number of ESALs to failure, $X = X_0 \cdot \exp(-m \cdot T)$, depends on L (the smaller L, the smaller X).

Equation (10) shows that n does not depend on L . Assume that $n \cdot T_C$ is strictly less than T_R (or, equivalently, that X_R is not a multiple of X_C). This assumption avoids the situation where both types of activities occur at the same time. If that situation were to happen, any reasonable highway agency would choose to perform type-R activity only at that time. More generally, a highway agency might decide to skip each type-C activity that precedes a type-R activity by a very short period, e.g. less than 3 months.

Let U_C and U_R be the unit costs (\$/mile) for type-C and type-R activities, respectively. Fig. 2 shows a possible cash flow diagram for all future activities (in this example, $n=2$). Present time is time 0. It is assumed that a type-R activity took place just before time 0, which is acceptable for comparative analysis.

In order to simplify notation, define a *cycle* as the time period starting at, and including, a type-R activity and ending at, but not including, the next type-R activity. Let r , such that $r>0$, be the discount rate per annum. Let U_{cycle} be the equivalent unit cost for a cycle, evaluated at the beginning of the cycle. Equation (11) gives the expression for it using continuous discounting. The example in Fig. 3 is equivalent to the one in Fig. 2, i.e. they both have the same present value (at time 0) of all future costs.

$$U_{cycle} = U_R + U_C \cdot \sum_{i=1}^n \exp(-r \cdot T_C \cdot i) \quad (11)$$

Let V be the present value of all future type-C and type-R activities (\$/mile).

$$V = U_C \cdot \sum_{i=1}^n \exp(-r \cdot T_C \cdot i) + U_{cycle} \cdot \sum_{j=1}^{\infty} \exp(-r \cdot T_R \cdot j) \quad (12)$$

But,

$$\sum_{j=1}^{\infty} \exp(-r \cdot T_R \cdot j) = \sum_{j=1}^{\infty} (\exp(-r \cdot T_R))^j = \frac{\exp(-r \cdot T_R)}{1 - \exp(-r \cdot T_R)} = \frac{1}{\exp(r \cdot T_R) - 1} \quad (13)$$

The second equality in Equation (13) comes from the assumption that $(-r \cdot T_R)$ is strictly negative and finite. As a result of this assumption, $0 < \exp(-r \cdot T_R) < 1$. Therefore, the infinite geometric series converges. Then, using Equations (12) and (13):

$$V = U_C \cdot \sum_{i=1}^n \exp(-r \cdot T_C \cdot i) + \frac{U_{cycle}}{\exp(r \cdot T_R) - 1} \quad (14)$$

By substituting the expression for U_{cycle} from Equation (11) into Equation (14):

$$V = U_C \cdot \sum_{i=1}^n \exp(-r \cdot T_C \cdot i) + \frac{U_R + U_C \cdot \sum_{i=1}^n \exp(-r \cdot T_C \cdot i)}{\exp(r \cdot T_R) - 1} \quad (15)$$

Using the assumption that $n \cdot T_C$ is strictly less than T_R , an infinitesimal change in either T_C or T_R does not change the value of n . Then, using Equation (15), we obtain:

$$\frac{\partial V}{\partial T_C} = -U_C \cdot r \cdot \sum_{i=1}^n i \cdot \exp(-r \cdot T_C \cdot i) - \frac{U_C \cdot r}{\exp(r \cdot T_R) - 1} \cdot \sum_{i=1}^n i \cdot \exp(-r \cdot T_C \cdot i) \quad (16)$$

Simplifying:

$$\frac{\partial V}{\partial T_C} = -U_C \cdot r \cdot \left(\sum_{i=1}^n i \cdot \exp(-r \cdot T_C \cdot i) \right) \cdot \left(\frac{\exp(r \cdot T_R)}{\exp(r \cdot T_R) - 1} \right) \quad (17)$$

Also, using Equation (15):

$$\frac{\partial V}{\partial T_R} = \frac{-r \cdot \exp(r \cdot T_R) \cdot \left(U_R + U_C \cdot \sum_{i=1}^n \exp(-r \cdot T_C \cdot i) \right)}{(\exp(r \cdot T_R) - 1)^2} \quad (18)$$

Using Equation (8):

$$\frac{dT_C}{dL} = \frac{-X_C}{L^2} \quad (19)$$

Using Equation (9):

$$\frac{dT_R}{dL} = \frac{-X_R}{L^2} \quad (20)$$

Suppose that the additional ESAL is defined as a *recurring additional ESAL* (Lindberg 2002; Small et al. 1989; Vitaliano and Held 1990). Using continuous discounting, the annualized cost of all future MR&R activities equals $(e^r-1) \cdot V$. Then, the MR&R marginal cost (\$/ESAL/mile) equals:

$$C' = \frac{d((e^r - 1)V)}{dL} = (e^r - 1) \frac{dV}{dL} \quad (21)$$

Using the Chain Rule:

$$C' = (e^r - 1) \left(\frac{\partial V}{\partial T_C} \cdot \frac{dT_C}{dL} + \frac{\partial V}{\partial T_R} \cdot \frac{dT_R}{dL} \right) \quad (22)$$

Where, the derivatives on the right-hand side are given by Equations (17), (18), (19) and (20).

Instead of using particular pavement structure and climate data, particular pavement deterioration models, and particular maintenance strategies (trigger levels and intensities for activities C and R), this study assumes a realistic MR&R strategy and parametrically varies the inputs X_C , X_R , L , U_C , U_R and r . For each instance, the realistic marginal cost, which takes into account both activities and their interdependence, is computed and compared with the marginal cost estimates that take into account only one type of MR&R activity (C or R), and with the marginal cost estimate that takes into account both activities but ignores their interdependence.

Computations

Table 1 shows the default values for the input variables used in the computations. In order to understand the effect of the input variables, each will be varied, while fixing the others to the values shown in Table 1 (unless otherwise noted).

The following four quantities will be computed:

- The realistic MR&R marginal cost, as given by Equation (22).
- The MR&R marginal cost that assumes that only activity C is performed in response to cracking, as given by Equation (7) with $U=U_C$ and $X=X_C$. Such an MR&R strategy leads to unacceptable levels of rutting.
- The MR&R marginal cost that assumes that only activity R is performed in response to rutting, as given by Equation (7) with $U=U_R$ and $X=X_R$. Such an MR&R strategy leads to unacceptable levels of cracking.
- The sum of the MR&R marginal costs for the two single-activity strategies. This sum is expected to be larger than the realistic MR&R marginal cost, since it fails to take into account the beneficial effect of activity R on cracking.

First, the effect of varying the frequencies of activities C and R will be studied. These frequencies are affected by the values of L, X_C and X_R . Fig. 4 shows that as L increases, all four marginal cost estimates increase asymptotically to constant values. It is easiest to understand this for the case of the MR&R marginal cost for a single-activity strategy, which is given by Equation (7). It can be shown that the asymptotic value equals:

$$\lim_{L \rightarrow \infty} (C'_{simple}) = \frac{(e^r - 1)U}{r \cdot X} \quad (23)$$

For small values of r , this asymptotic value is approximately U/X (\$/ESAL/mile), which Newbery (1988) calls the “average maintenance cost”, and Small et al. (1989, p. 15) call the “naïve” MR&R marginal cost.

In Fig. 4, the difference between ‘Simple MC with R’ and ‘Sum of simple MCs’ represents the importance of taking into account the less costly activity C, and the difference between ‘Sum of simple MCs’ and ‘Realistic MC’ represents the effect of interdependence between the two activities. Fig. 4 shows that as L increases, the sizes of these two differences increase slightly. In other words, as L increases, it becomes more important to take into account the less costly activity and the interdependence, but the change in importance is small.

Fig. 5 shows the effects of varying X_C . When X_C increases, the frequency of activity C decreases (but the frequency of activity R is not affected). As a result, the MR&R marginal cost for the strategy that uses only C decreases, the MR&R marginal cost for the strategy that uses only R does not change, and the realistic MR&R marginal cost decreases. The realistic MR&R marginal cost has drops at the values of X_C that are divisors of $X_R=500,000$. For example, a drop occurs at $X_C=250,000$. For values of X_C slightly above 250,000, the highway agency performs only one type-C activity between each pair of type-R activities. For values of X_C slightly below 250,000, the highway agency performs two type-C activities between each pair of type-R activities. (In real life, a reasonable highway agency would not perform the second type-C activity; instead, it would wait for the soon-to-come type-R activity). As aforementioned, the model assumes that X_C is not a divisor of X_R . Therefore, the realistic marginal cost is not defined for such values of X_C . If we had allowed X_C to be a divisor of X_R , each type-R activity would coincide with the last type-C activity of the previous cycle, eliminating the beneficial effect of activity R on cracking. As a result, the value of the realistic MR&R marginal cost would

coincide with the value of the sum of the simple marginal costs (the two curves touch, as shown in Fig. 5).

Although the realistic marginal cost curve in Fig. 5 appears to have horizontal segments, these segments are in fact downward sloping. The segments are nearly horizontal since each of them corresponds to a constant value of n (i.e. constant number of type-C activities per cycle). Changing X_C within each segment can only vary the times of the type-C activities by less than T_R [or, to be more exact, by less than T_R/n minus $T_R/(n+1)$]. With small values of r ($r=0.05$), this has an insignificant effect of the marginal cost. However, as the value of r increases, the slopes of these segments become more pronounced, as shown in Fig. 6, which uses an unrealistically high $r=0.40$ in order to clearly show the slope.

When X_C exceeds X_R , i.e. when activity R becomes more frequent than activity C (which violates one of the model assumptions), activity C is never triggered and therefore never takes place.

Fig. 7 shows the effect of varying X_R . When X_R increases, the frequency of activity R decreases (but T_C is not affected). As a result, the MR&R marginal cost for the strategy that uses only R decreases, and the MR&R marginal cost for the strategy that uses only C does not change. Furthermore, the realistic MR&R marginal cost decreases, as long as n remains constant. The realistic MR&R marginal cost has jumps at the values of X_R that are multiples of $X_C=200,000$, since the number of type-C activities per cycle (n) increases by one at such values. As aforementioned, the model assumes that X_R is not a multiple of X_C . Therefore, the realistic marginal cost is not defined for such values of X_R .

Next, the effects of varying the activity unit costs and discount rate are examined. Changing both unit costs, U_C and U_R , by the same positive (multiplicative) factor α simply

changes the four marginal cost quantities by that same factor α . This fact can be easily seen from the equations for C' and C'_{simple} , and is illustrated by an example in Table 2. Therefore, it is not interesting to proportionately change both activity unit costs. Rather, it is more interesting to vary the relative value of one of them with respect to the other.

Fig. 8 shows the effect of varying U_C . As the value of U_C increases (the ratio of U_C to U_R increases), the difference between the realistic MR&R marginal cost and the sum of the simple marginal costs increases; in other words, it becomes more important to take into account the interdependence of the two MR&R activities.

When U_C exceeds U_R , a highway agency might decide to rely solely on type-R activities, which will be performed at intervals of length T_C (in other words, cracking triggers activity R). The model does *not* capture this possible strategy, which leads to a different value of marginal cost (this value is given by the line labeled 'MC with R triggered by cracking' in Fig. 8). Therefore, the model should *not* be used to estimate the 'realistic marginal cost' in cases where the highway agency might use a different MR&R strategy from what the model assumes.

Fig. 9 shows the effect of r on the marginal cost values. The difference between the realistic MR&R marginal cost and the sum of the simple marginal costs is insensitive to r . However, the difference is sensitive to r for lower values of L , as Fig. 10 shows (this example corresponds to large values of T_C and T_R).

Conclusions

In the highway maintenance cost literature, the perpetual overlay indirect approach is often used to estimate maintenance marginal cost. This approach is based on the assumption that a highway agency only uses one type of MR&R activities, namely overlays. This paper relaxes this assumption by presenting a methodology for estimating MR&R marginal cost for a strategy with

two MR&R activities, C and R, which are carried out in response to two different measures of pavement condition. It is assumed that activity C only improves one measure of pavement condition, while activity R improves both. Activity C is assumed to be more frequent than activity R. Furthermore, activity C is assumed to have a lower unit cost than activity R.

Our computations show that the realistic MR&R marginal cost estimates (realistic MC) are significantly higher than the MR&R marginal cost estimates that account only for the “dominant” activity R (simple MC with R). This difference becomes more significant when activity C becomes relatively more frequent, or relatively more expensive. In other words, simple MC with R is a lower bound for realistic MC, a bound that is typically not tight. Therefore, both activities should be taken into account when estimating MR&R marginal cost.

The sum of the two simple estimates of MR&R marginal cost that take into account only one activity (sum of simple MCs) does not capture all the pavement condition improvements resulting from activity R. As a result, the sum of simple MCs is an upper bound for the realistic MC. This can be understood intuitively. Each activity R, which is performed in order to improve rutting, has a positive effect on cracking, in that it reduces cracking that has accumulated since the last type-C activity. As a result, the realistic MC is lower than the sum of simple MCs. Furthermore, the longer this time period between a type-R activity and the type-C activity immediately preceding it, the larger the difference between the sum of simple MCs and the realistic MC.

A factor that affects the tightness of this upper bound is the ratio of unit costs. As U_C/U_R increases, the difference between the sum of simple MCs and the realistic MC increases, and it becomes more important to take into account the interdependence of the two activities.

Now, the answers to the two questions posed in the introduction of this paper can be summarized. First, is it acceptable to ignore the less costly MR&R activity? The simple MC with R underestimates the realistic MC, and the difference is often significant. Therefore, the less costly activity C should not be ignored. Second, if both MR&R activities are to be considered, is it acceptable to ignore their interdependence? Although the sum of simple MCs is often close to the realistic MC, it consistently overestimates it, and the difference can be significant in some cases. Therefore, the interdependence cannot be ignored either.

Since each highway agency has a different MR&R strategy, MR&R unit costs and pavement deterioration, it is difficult to generalize the results. However, we present a methodology, which can be modified and extended in order to analyze different situations. From a practical point of view, the highway agency should first find the realistic MR&R marginal cost, and then check whether it makes a significant difference to ignore less costly activity types or ignore the interdependence between different activity types. In other words, it should not ignore activities or interdependence unless it can justify doing so for that specific situation.

In order to extend this study, future work might look at MR&R strategies that include more than two activities, as well as more complex interdependence relationships, such as partial improvement. Furthermore, the effect of weathering might be included.

Finally, the authors have worked on relaxing two other assumptions made in the perpetual overlay approach. One assumption is that pavement deterioration caused by an axle is proportional to the fourth power of the axle load irrespective of the performance indicator used by the highway agency to trigger maintenance. The other is that pavement deterioration is deterministic, and as a result, the exact times of all future MR&R activities can be (exactly) predicted (Anani 2008).

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Notation

The paper uses the following symbols:

- C = A type of MR&R activity which is triggered by cracking
- C' = MR&R marginal cost (\$/ESAL/mile)
- C'_{simple} = MR&R marginal cost (\$/ESAL/mile) for case of single activity type
- L = Annual traffic loading (ESAL/year)
- N = Number of times a type-C activity is performed between two consecutive type-R activities
- r = Discount rate per annum
- R = A type of MR&R activity which is triggered by rutting
- T = Time (in years) between two consecutive activities for case of single activity type
- T_C = Time (in years) between any two consecutive type-C activities that do not have a type-R activity between them
- T_R = Time (in years) between any two consecutive type-R activities
- U = Unit cost for activity (\$/mile) for case of single activity type
- U_C = Unit cost for activity C (\$/mile)
- U_{cycle} = Equivalent unit cost for a *cycle*, evaluated at the beginning of the cycle (\$/mile)
- U_R = Unit cost for activity R (\$/mile)
- V = Present value of all future type-C and type-R activities (\$/mile)
- X = Number of ESALs to failure for case of single activity type
- X_C = Number of ESALs to failure for activity C
- X_R = Number of ESALs to failure for activity R

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Tables

Table 1- default input values used in computations

Input variable	Description/units	Default value
X _C	ESALs to failure for activity C	200,000
X _R	ESALs to failure for activity R	500,000
L	Annual traffic loading (ESAL/year)	100,000
U _C	Unit cost for activity C (\$/mile)	20,000
U _R	Unit cost for activity R (\$/mile)	200,000
r	Discount rate per annum	0.05

Table 2- proportionately changing activity unit costs

Inputs						Results			
X_C	X_R	L	U_C	U_R	R	N	Marginal cost (\$/ESAL/mile)		
							C and R activities	Only C activity	Only R activity
200,000	500,000	100,000	10,000	100,000	0.05	2	0.2451	0.0512	0.2040
200,000	500,000	100,000	20,000	200,000	0.05	2	0.4902	0.1025	0.4080

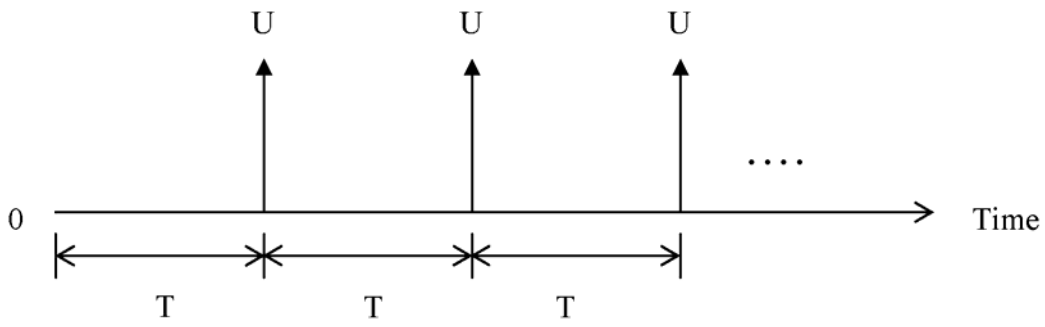


Fig. 1. Future MR&R costs (with one type of activity)

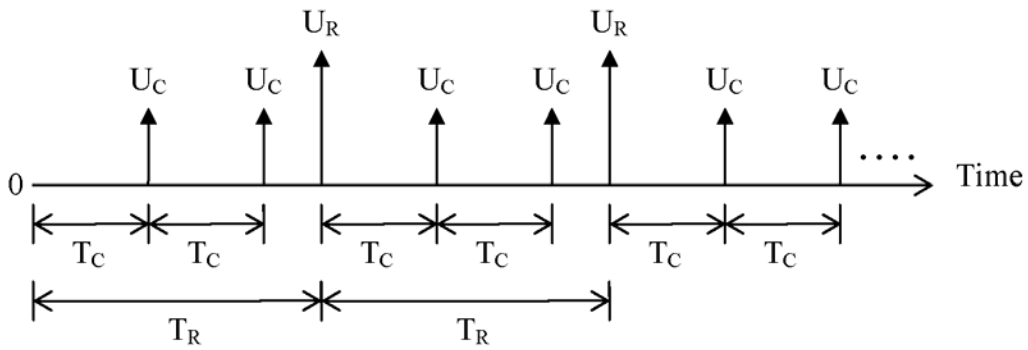


Fig. 2. Example of future MR&R costs (n=2)

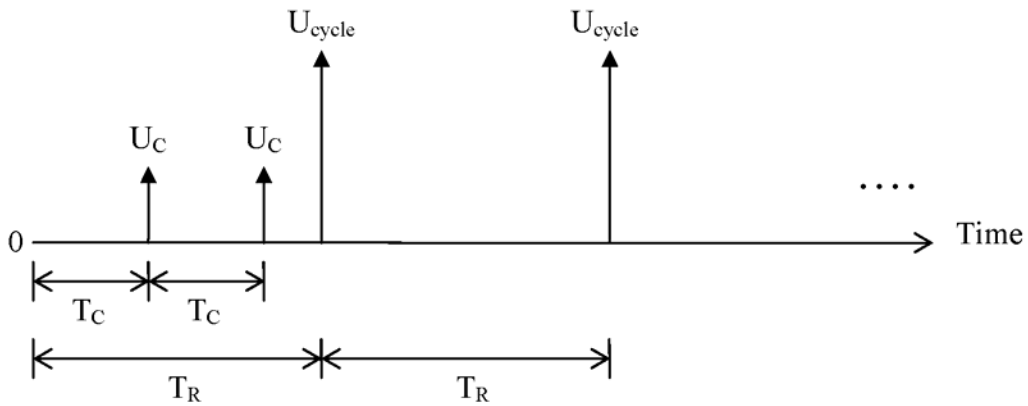


Fig. 3. Equivalent MR&R costs for previous example (n=2)

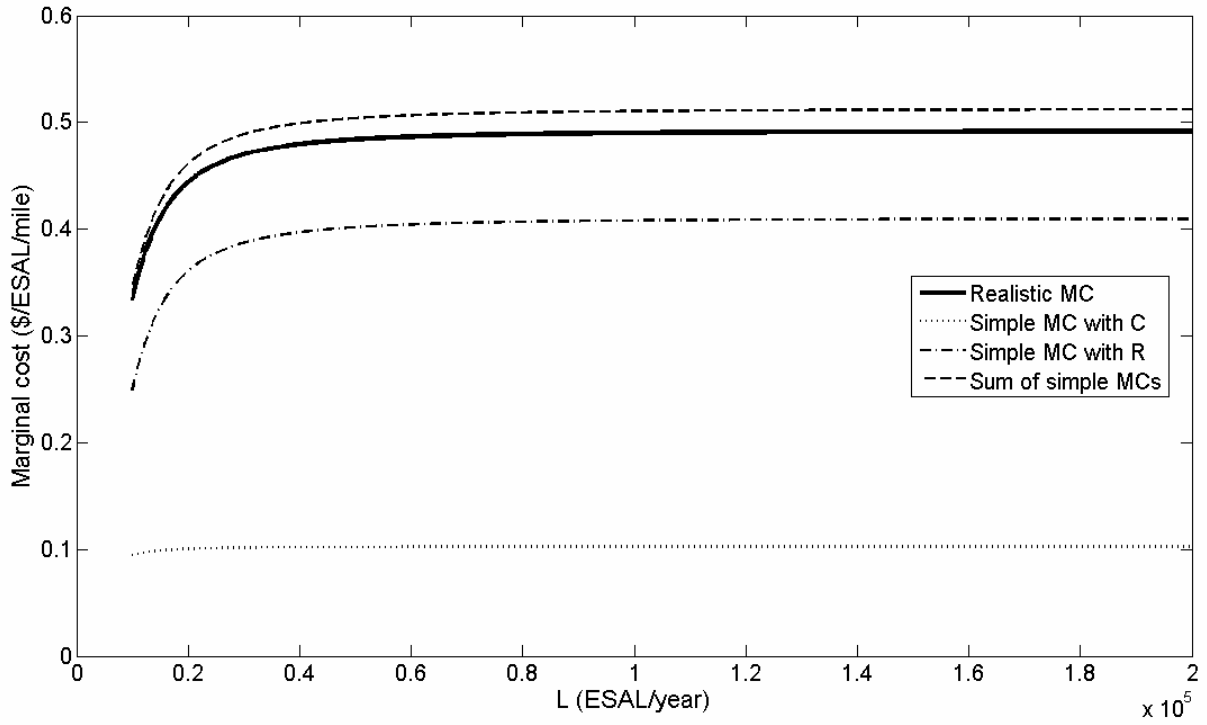


Fig. 4. Varying annual traffic loading

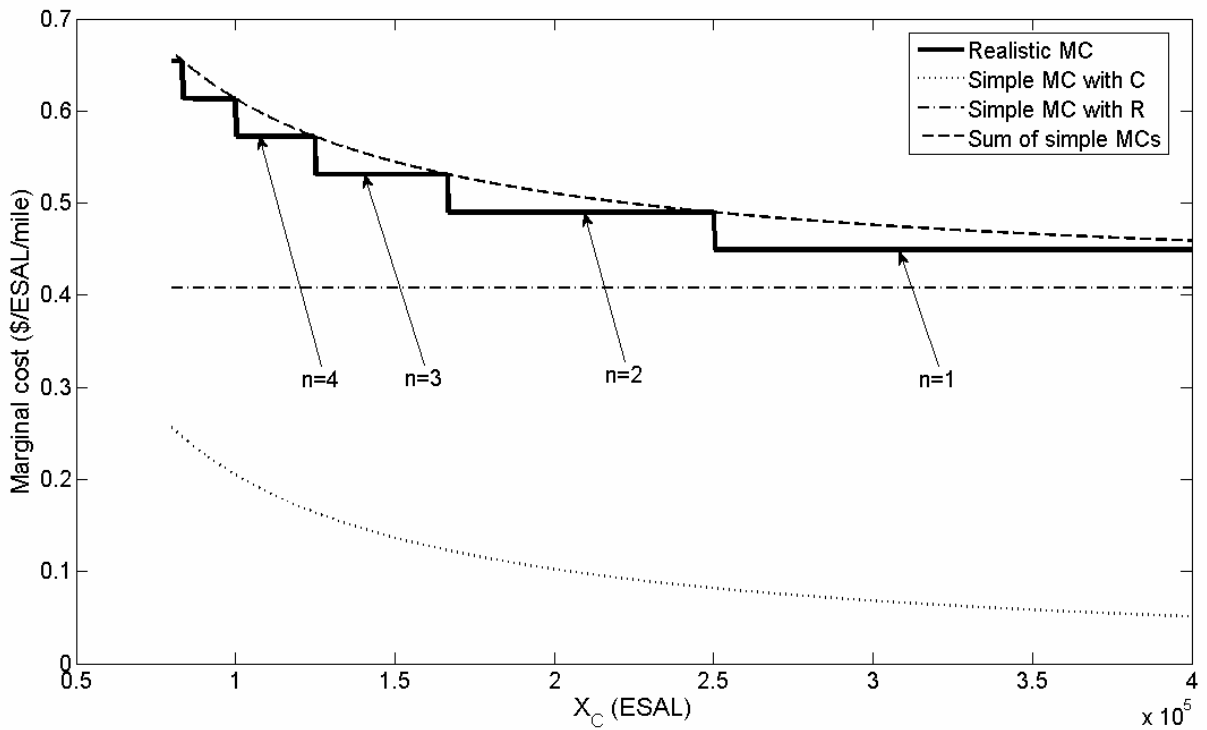


Fig. 5. Varying ESALs to failure for activity C

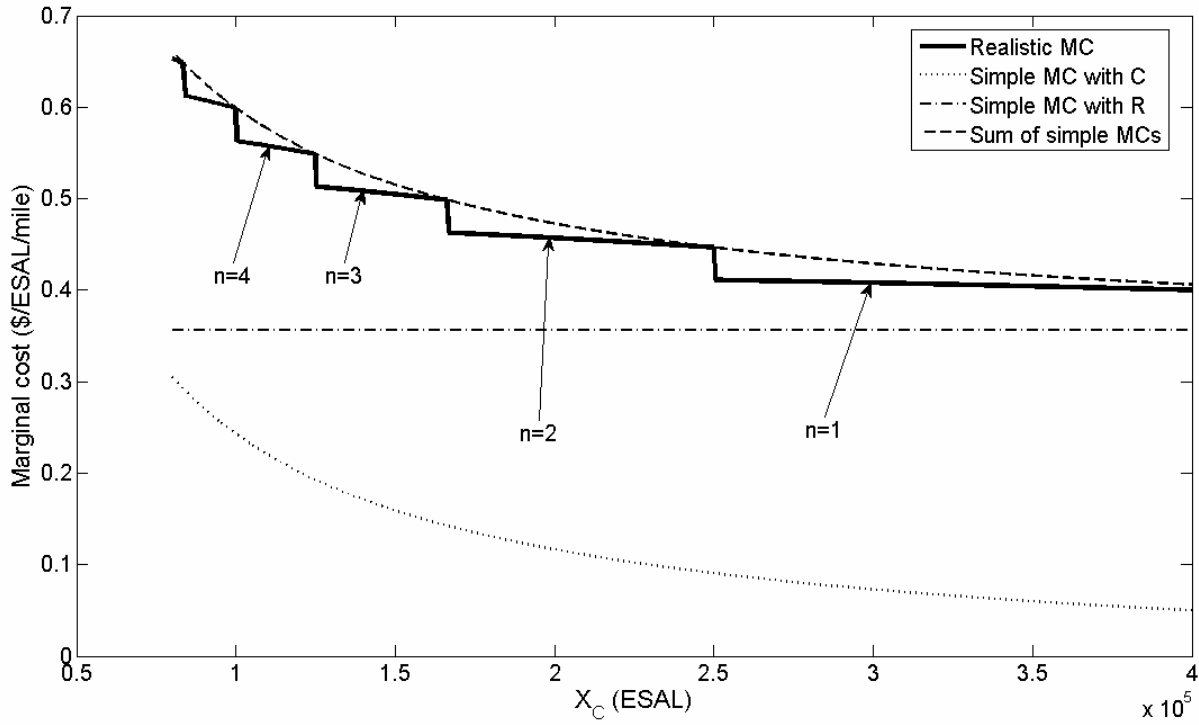


Fig. 6. Varying ESALs to failure for activity C (higher $r=0.40$)

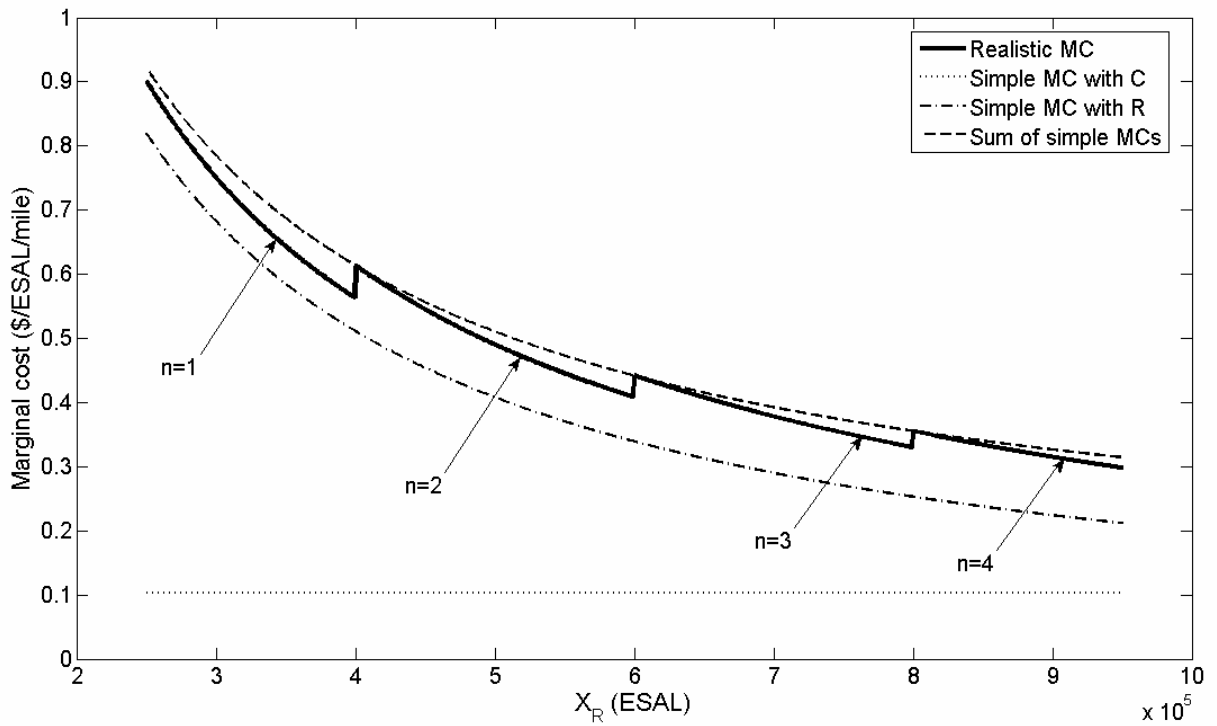


Fig. 7. Varying ESALs to failure for activity R

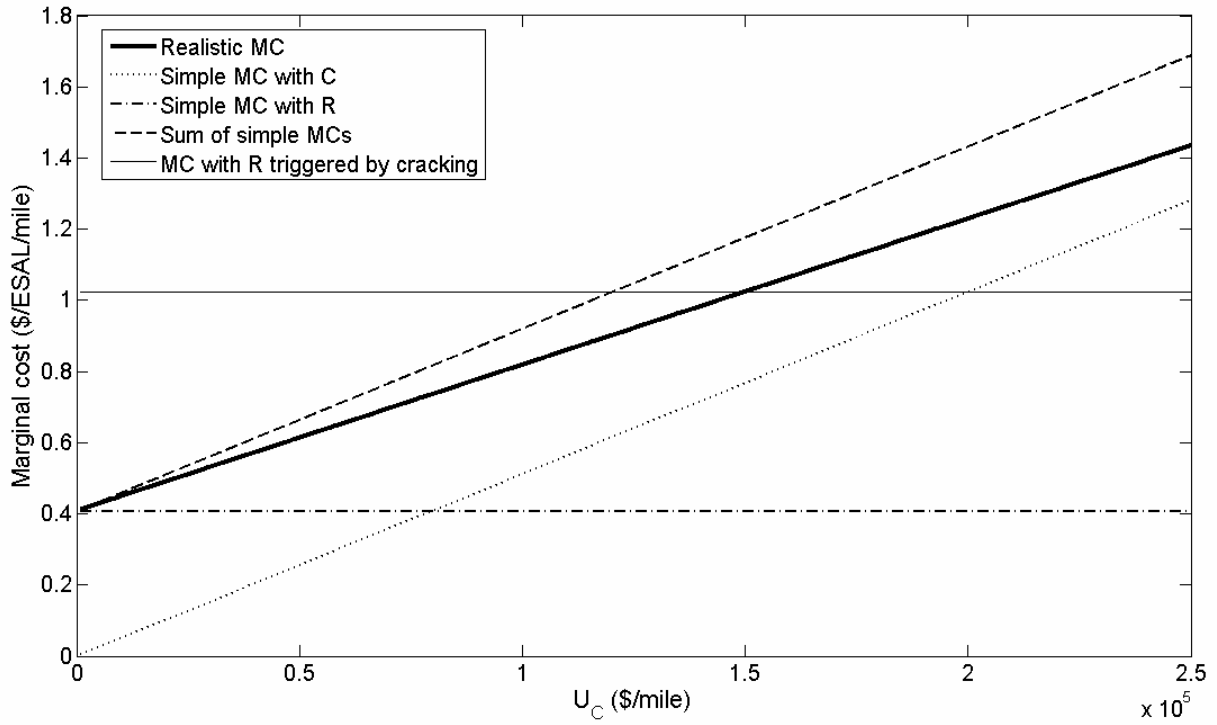


Fig. 8. Varying unit cost for activity C

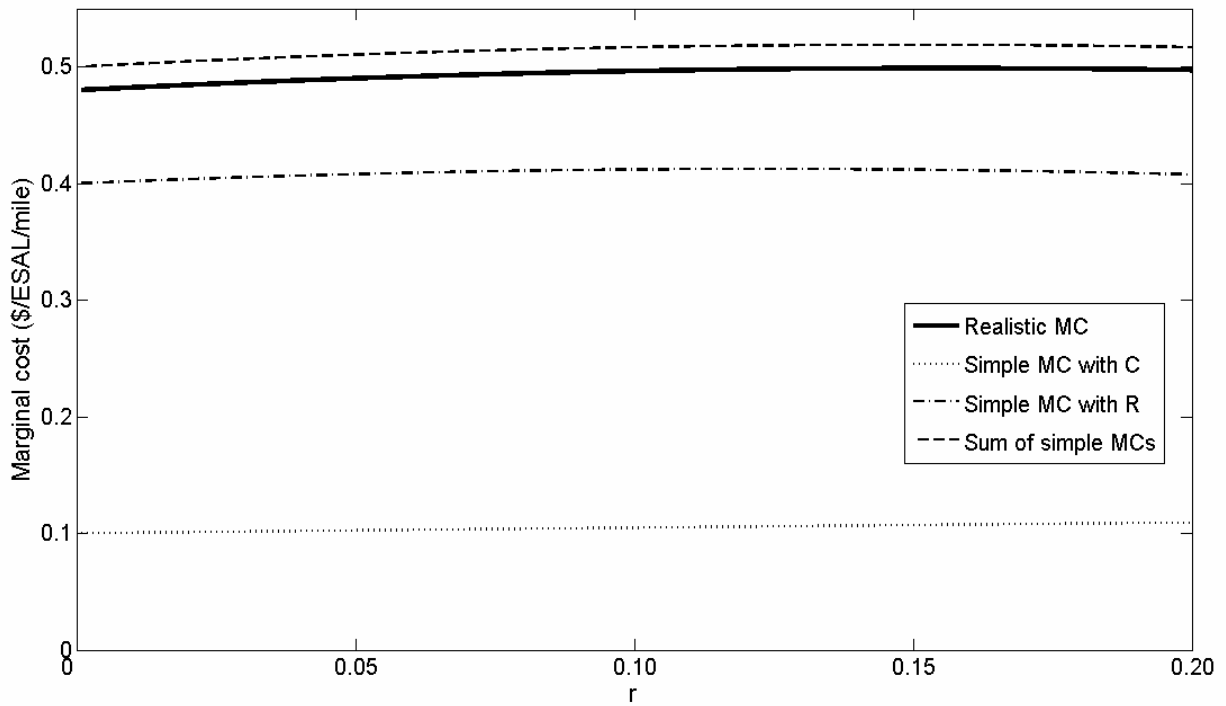


Fig. 9. Varying discount rate per annum

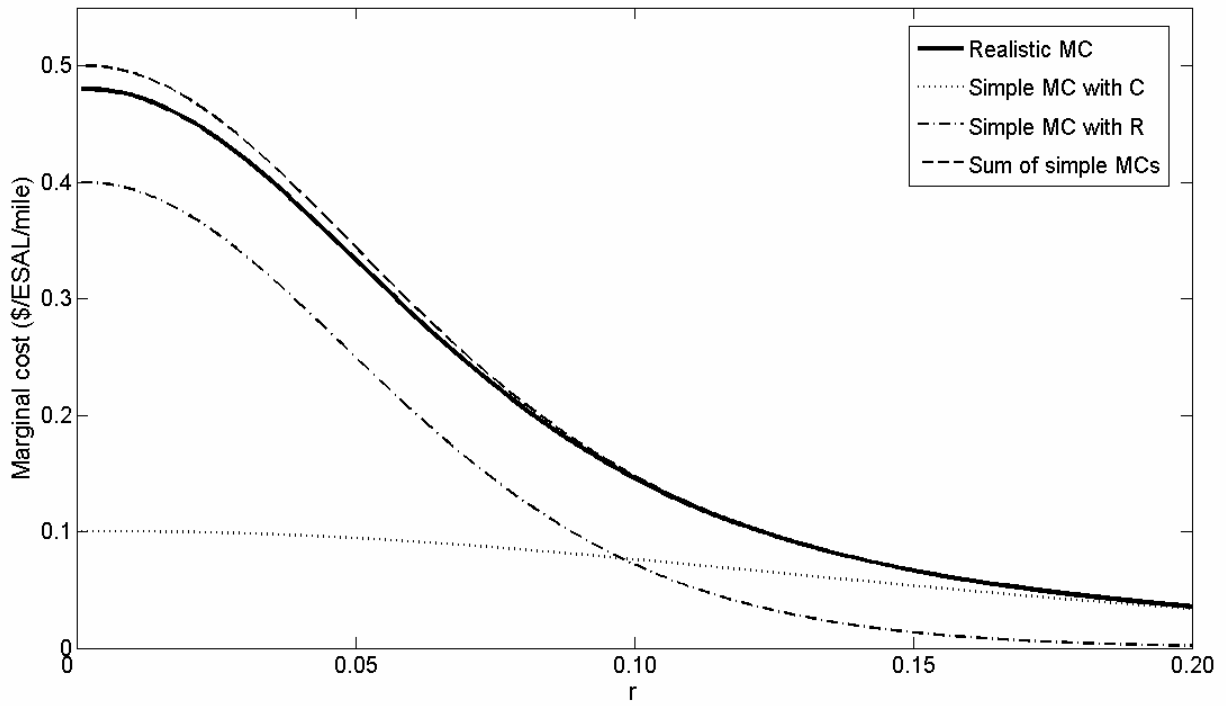


Fig. 10. Varying discount rate per annum (lower L=10,000)