OPTIMUM LENGTH OF TWO-LANE, TWO-WAY, NO-PASSING TRAFFIC OPERATION IN CONSTRUCTION/MAINTENANCE ZONES ON RURAL FOUR-LANE DIVIDED HIGHWAYS

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ABSTRACT

The objective of the study was to determine the optimum length of two-lane, two-way, no-passing traffic operation in construction/maintenance zones on rural four-lane divided highways. An equation was developed for the sum of road-user and traffic-control costs as a function of this length. The methods of calculus were then used to derive the optimum length that would minimize the sum of road-user and traffic-control costs. The optimum length equation derived can be used in the planning and design of crossover-type traffic control systems for construction/maintenance zones on rural four-land divided highways.

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INTRODUCTION

One method of traffic control in construction/maintenance zones on rural four-lane divided highways is to close one roadway and have two-lane, two-way, no-passing traffic operation on the other. The closed roadway is cleared for construction/maintenance work and traffic is diverted from it across the median to the other roadway which is signed and marked for two-lane, two-way, no-passing traffic operation. A typical application of this type of control is illustrated in Figure 1.

Because of the number of severe head-on accidents that have been experienced with this type of control, special attention has been given to improving the design and use of delineation devices, pavement markings, and signing to separate and warn the opposing lanes of traffic. Also, there has been some concern about the apparent effect of the length of two-lane, two-way, no-passing operations on traffic safety. Intuitively, the greater this length, the greater the delay and frustration caused by slower moving vehicles; thus the greater the temptation to pass and increase the potential for head-on accidents. Based on inspection reports and project reviews, the Federal Highway Administration has recommended the use of minimum lengths (three to five miles maximum).[1]

However, despite the above argument for minimum lengths of two-lane, two-way, no-passing operations, there are also reasons for considering the use of longer lengths. The use of longer lengths within a given construction/maintenance area would reduce the number of median crossovers that would be required. The construction, signing, and marking of fewer crossovers would reduce traffic control costs. Consequently for a given construction/maintenance project, the minimum

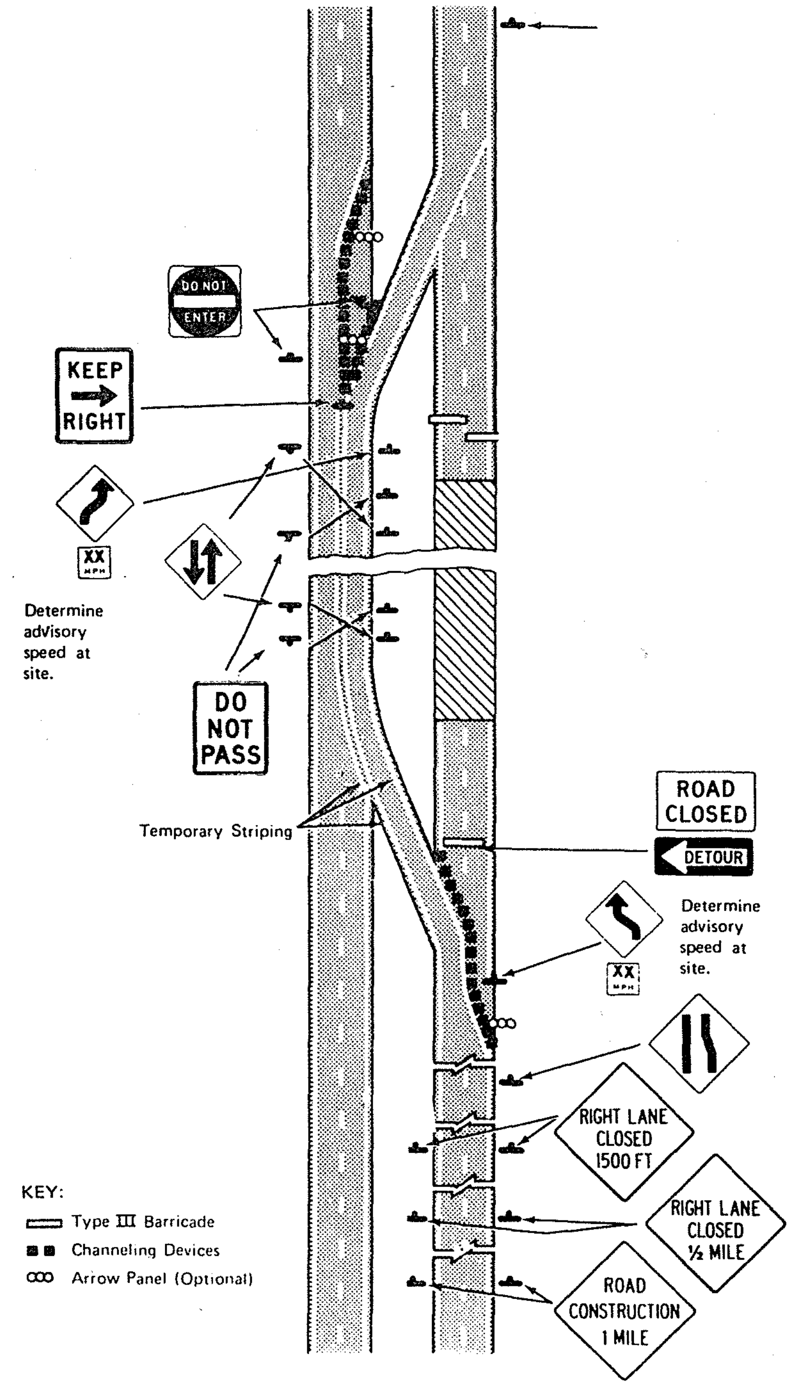


Figure 1 Typical Application of Crossover Control. (Source: MUTCD, 1978, page 6B-10)

length of two-lane, two-way, no-passing operation is not necessarily the optimum. Although minimum length reduces road user costs, it increases the cost of traffic control. Therefore, to determine the optimum length, the tradeoffs between the safety and efficiency of traffic flow and the costs of traffic control must be evaluated.

OBJECTIVE

The objective of this study was to determine the optimum length of two-lane, two-way, no-passing traffic operation in construction/maintenance zones on rural four-lane divided highways. An equation was developed for the sum of road-user and traffic-control costs as a function of this length. The methods of calculus were then applied to derive the optimum length that would minimize the sum of road-user and traffic-control costs.

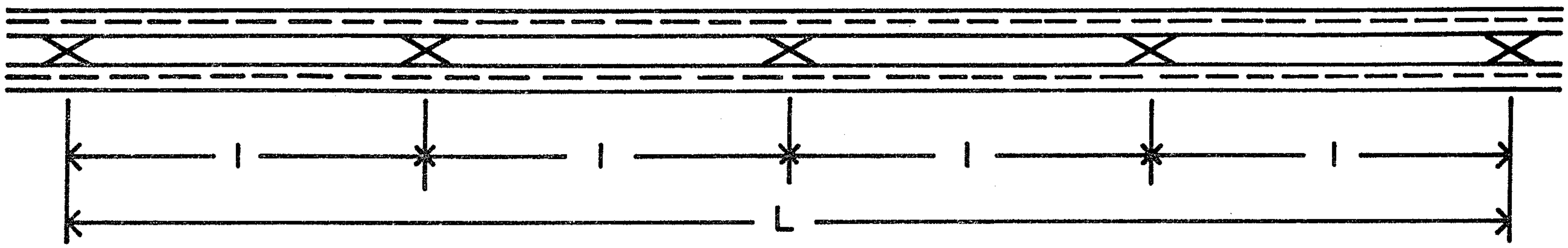
This paper presents the derivation of the optimum length equation. Also included are the results of its evaluation for various average daily traffic volumes and project durations, which illustrate typical ranges in the optimum length.

PROBLEM STATEMENT

The problem addressed by this study is illustrated in Figure 2 and can be briefly stated as follows:

(1) given a construction/maintenance project of a certain length (L) and duration (D) on a rural four-lane divided highway with a particular average daily traffic volume (ADT);

(2) find the length (ℓ) of two-lane, two-way, no-passing traffic operation that will minimize the sum of the road-user and traffic control costs.



L — length of construction / maintenance project

l — segment length

X — crossover system

Figure 2 Division of Construction / Maintenance Project on Four - Lane Divided Highway Into Equal - Length Crossover Segments.

During the life of the project, work is conducted in only one segment at a time, with construction/maintenance on one roadway and two-lane, two-way, no-passing traffic operation on the other. After the work is completed on the one roadway, the traffic is switched onto that side and work begins on the opposite roadway. When work is finished in one segment, it is returned to four-lane divided operation and work is started in another segment until the project is completed. Project duration as defined here is the expected time it would take to complete the actual construction/maintenance work. It does not include time to construct the crossover systems or to implement other traffic control measures.

The number of segments (N) into which a project is divided is equal to the project length (L) divided by the segment length (ℓ). At each end of a segment is a crossover system which is composed of two median crossovers, one for each direction of traffic flow. Therefore, the number of crossover systems (N_x) required is equal to the number of segments (N) plus one. These relationships are summarized as follows:

$$N = \frac{L}{\ell} \qquad \text{---Eq. 1}$$

$$N_x = N + 1 = \frac{L}{\ell} + 1 \qquad \text{---Eq. 2}$$

where N = number of segments,

L = project length (miles),

ℓ = segment length (miles),

N_x = number of crossover systems.

Obviously, only integer values of N have practical significance.

ROAD USER COSTS

The road user costs considered in this study were accident costs, delay costs, and operating costs. A brief discussion of each of these costs as a function of segment length follows.

Accident Costs

For the purpose of this study traffic accidents on a segment were classified as either crossover accidents or segment accidents. Crossover accidents are those which occur at the crossovers or on the approaches to them. Segment accidents are those which occur on the segment itself.

The cost of crossover accidents for the duration of a construction/maintenance project is:

$$C_{Ax} = c_{ax} a_x \frac{ADT}{10^8} D \qquad \text{---Eq. 3}$$

where C_{Ax} = crossover accident cost for project (dollars),

c_{ax} = average cost per crossover accident (dollars),

a_x = crossover accident rate (accidents per 100 million entering vehicles),

ADT = average daily traffic volume (vehicles per day),

D = project duration (days).

The average cost per crossover accident is a function of the severity of crossover accidents and the accident cost associated with each level of severity. A study conducted by Pang[(2)] of accidents in construction zones on I-80 in Nebraska, in which two-lane, two-way, no-passing traffic operation was used, found the severity of crossovers accidents to be: 0%-fatal, 38%-non-fatal injury, and 62%-property damage only. Applying these severities to the following accident costs, which are presented in the participant notebook[(3)] for the National Highway Institute (NHI) training course on construction zone traffic control, the average cost per crossover accident is computed to be $2,600:

- $142,000 per fatal accident
- $ 4,500 per non-fatal-injury accident
- $ 1,400 per property-damage-only accident

Pang(2) also found that the crossover accident rate was 167.4 accidents per 100 million entering vehicles.

The cost of segment accidents for the duration of a construction/maintenance project is:

$$C_{A\ell} = c_{a\ell} a_{\ell} \frac{ADT}{10^8} D\ell \qquad \text{---Eq. 4}$$

where $C_{A\ell}$ = segment accident cost for project (dollars),

$c_{a\ell}$ = average cost per segment accident (dollars),

a_{ℓ} = segment accident rate (accidents per 100 million vehicle miles),

ADT = average daily traffic volume (vehicles per day),

D = project duration (days),

ℓ = segment length (miles).

All segment accidents studied by Pang(2) were found to be fatal accidents, which indicates that these accidents are usually more severe than crossover accidents. Application of a 100%-fatal severity to the above accident costs yields an average cost per segment accident of $142,000. Pang(2) also found the segment accident rate was 21.2 accidents per 100 million vehicle miles.

Thus the total accident costs (C_A) for the duration of a construction/maintenance project is the sum of Equations 3 and 4:

$$C_A = \frac{ADT}{10^8} D \left(c_{ax} a_x + c_{a\ell} a_{\ell} \ell\right) \qquad \text{---Eq. 5}$$

Delay Cost

Delay cost to a road user is the value of time lost while traveling through a construction/maintenance zone. The time lost is a function of the difference between the average overall speed of the two-lane, two-way, no-passing operation and that of the normal four-lane divided operation. The total delay cost for the duration of a construction/maintenance project is:

$$C_D = c_T \left(\frac{\ell}{v_\ell} - \frac{\ell}{v_o}\right) \cdot ADT \cdot D \qquad \text{---Eq. 6}$$

where C_D = total project delay cost (dollars),

c_T = value of time (dollars per vehicle-hour),

ℓ = segment length (miles),

v_ℓ = average overall speed of two-lane, two-way, no-passing operation (mph),

v_o = average overall speed of four-lane, divided operation (mph),

ADT = average daily traffic volume (vehicles per day),

D = project duration (days).

The value of time in dollars per vehicle presented in the NHI participant notebook can be approximated by the following relationship:

$$C_T' = 5 \left(\frac{\ell}{v_\ell} - \frac{\ell}{v_o}\right) \qquad \text{---Eq. 7}$$

where C_T' = value of time (dollars per vehicle).

Therefore, c_T = 5 dollars per vehicle hour ---Eq. 8

Substituting Equation 8 into Equation 6, the total delay cost equation becomes:

$$C_D = 5\,\ell \left(\frac{1}{v} - \frac{1}{v_o}\right) ADT\ D \qquad \text{---Eq. 9}$$

It should be noted that the average overall speeds, v_ℓ and v_o, are weighted averages based on the numbers of vehicles expected to travel at each overall speed during an average day. Lower overall speeds during periods of congestion would be given more weight than higher overall speeds during periods of free flow. Thus the average overall speeds used in Equation 9 should account for the influence of the variation in volume-to-capacity ratios throughout an average day.

Operating Costs

For the purpose of this study operating costs include speed-change-cycle cost as well as fuel, oil, tire, maintenance, and depreciation costs. The speed-change-cycle cost is the excess operating cost that results from a speed-change cycle that might be required when going from the four-lane divided traffic operation to the two-lane, two-way, no-passing operation and returning to the four-lane divided operation. The speed-change-cycle cost varies directly with the magnitude of the speed change and the initial speed from which it is made. The remainder of the operating costs can also be expressed as a function of speed. In addition, the operating costs must be adjusted for percent trucks, because they are dependent on vehicle size.

The total operating cost for the duration of a construction/maintenance project is:

$$C_o = ADT \cdot D\ (c_{ox} + c_{o\ell}\,\ell) \qquad \text{---Eq. 10}$$

where C_o = total project operating costs (dollars),

ADT = average daily traffic volume (vehicles per day),

D = project duration (days),

c_{ox} = average operating cost per speed-change cycle (dollars),

$c_{o\ell}$ = average operating cost per vehicle-mile (dollars),

ℓ = segment length (miles).

For a speed-change cycle of 55-45-55 mph, an operating speed of 45 mph, and 10 percent trucks, the average speed-change-cycle cost and average operating cost given in the NHI participant notebook[3] are $0.0108 per vehicle-speed-change cycle and $0.0996 per vehicle-mile, respectively.

TRAFFIC CONTROL COSTS

The cost of traffic control include the cost of constructing the crossover systems and the costs of the signs, pavement markings, and delineation devices used to warn, guide, regulate, and separate the opposing lanes of traffic. The total traffic control cost for the duration of a construction/maintenance project is:

$$C_{Tc} = N_x c_x + N c_\ell \ell \qquad \text{---Eq. 11}$$

where C_{Tc} = project traffic control costs (dollars),

N_x = number of crossover systems,

N = number of segments,

C_x = average cost of constructing crossover system and providing traffic control devices on the crossovers and their approaches (dollars per crossover system),

c_ℓ = average cost of traffic control devices on the segment (dollars per mile),

ℓ = segment length (miles).

Substituting Equations 1 and 2 into Equation 11, the total traffic control cost equation becomes:

$$C_{Tc} = L\left(\frac{c_x}{\ell} + c_\ell\right) + c_x \qquad \text{---Eq. 12}$$

In Nebraska, the average costs for crossover systems and segment traffic control are \$30,000 per crossover system and \$10,000 per mile, respectively.

TOTAL TRAFFIC OPERATION AND CONTROL COST

The total traffic operation and control cost associated with a two-lane, two-way, no-passing traffic operation in construction/maintenance zones on a rural, four-lane divided highway is the sum of the road user and traffic control costs described above. Therefore, by summing Equations 5, 9, 10 and 12, the total traffic operation and control costs for the duration of a construction/maintenance project is:

$$C = ADT \cdot D\left(10^{-8}(c_{ax}a_x + c_{a\ell}a_\ell\ell) + 5\ell\left(\frac{1}{v_\ell} - \frac{1}{v_o}\right) + c_{ox} + c_{o\ell}\ell\right)$$
$$+ L\left(\frac{c_x}{\ell} + c_\ell\right) + c_x \qquad \text{---Eq. 13}$$

where C = total project road user and traffic control cost (dollars),

ADT = average daily traffic volume (vehicles per day),

D = project duration (days),

L = project length (miles),

c_{ax} = average cost per crossover accident (dollars),

a_x = crossover accident rate (accidents per 100 million entering vehicles),

$c_{a\ell}$ = average cost per segment accident (dollars),

a_ℓ = segment accident rate (accidents per 100 million vehicle miles),

ℓ = segment length (miles),

v_ℓ = average overall speed of two-lane, two-way, no-passing operation (mph),

v_o = average overall speed of four-lane, divided operation (mph),

c_{ox} = average cost per vehicle-speed-change cycle (dollars),

$c_{o\ell}$ = average operating cost per vehicle-mile (dollars),

c_x = average cost of construction crossover system and providing traffic control devices on the crossovers and their approaches (dollars per crossover system),

c_ℓ = average cost of traffic control devices on the segment (dollars per mile).

OPTIMUM SEGMENT LENGTH

The optimum segment length is defined as the length of two-lane, two-way, no-passing traffic operation that minimizes the sum of the road user and traffic control costs for the duration of a construction/maintenance project. Therefore, by taking the derivative of Equation 13 with respect to segment length, equating it to zero, and solving for segment length, the optimum segment length is:

$$\ell_{opt} = \left[\frac{Lc_x/ADT \cdot D}{10^{-8}c_{a\ell}\,a_\ell + 5(\frac{1}{v_\ell} - \frac{1}{v_o}) + c_{o\ell}}\right]^{\frac{1}{2}} \quad \text{---Eq. 14}$$

where ℓ_{opt} = optimum segment length (miles),

ADT = average daily traffic volume (vehicles per day),

D = project duration (days),

L = project length (miles),

c_x = average cost of constructing crossover system and providing traffic control devices on the crossovers and their approaches (dollars per crossover system),

$c_{a\ell}$ = average cost per segment accident (dollars),

a_ℓ = segment accident rate (accidents per 100 million vehicle miles),

v_ℓ = average overall speed of two-lane, two-way, no-passing operation (mph),

v_o = average overall speed of four-lane, divided operation (mph),

$C_{o\ell}$ = average operating cost per vehicle-mile (dollars).

It should be noted that according to the second derivative test, Equation 14 defines the segment length that yields the minimum value of Equation 13. Also, the optimum segment length must always be less than or equal the project length. In other words, the minimum number of segments into which a project length can be divided is one.

In order to apply Equation 14 to a particular situation, all of the variables of which the optimum segment length is a function must first be determined. However, to illustrate typical ranges in optimum segment length, Equation 14 was evaluated for a six-mile project length and various combinations of average daily traffic volumes and project durations using the following values for the other independent variables:

c_x = \$30,000 per crossover system,

$c_{a\ell}$ = \$142,000 per segment accident,

a_ℓ = 21.2 segment accidents per 100 million vehicle-miles,

v_ℓ = 45 mph,

v_o = 55 mph.

$c_{o\ell}$ = \$0.0996 per vehicle-mile.

These values were intended to be representative of rural, four-lane, divided highways carrying 10 percent trucks. As described in previous sections of this paper, they were based on a study of construction zone accidents on I-80 in Nebraska by Pang [2] and data contained in the NHI participant notebook[3]. The results of this evaluation of Equation 14 are shown in Figure 3.

It is obvious that the optimum segment length for a given project length and set of unit costs, accident rates, and overall speeds is merely a function of the total number of vehicles that pass through the construction/maintenance zone throughout the project duration. The higher the number of vehicles passing through, the shorter the optimum segment length; because the increased cost of providing crossover systems is offset by a reduction in road user costs. However, as the total traffic volume approaches zero, the optimum segment length given in Equation 14 goes to infinity. But, as mentioned previously, the practical upper limit on segment length is the project length. Therefore, in cases of low traffic volumes where the optimum segment length computed with Equation 14 is greater than the project length, only one segment would be used.

Also, the optimum segment length computed using Equation 14 does not necessarily yield an integer number of segment lengths. When it does not, the total project road user and traffic control costs should be evaluated using Equation 13 for the two segment lengths which correspond to the integer number of segments on either side of the optimum-segment-length number of segments. For example, from Figure 3, the optimum segment length for an ADT of 10,000 and a project duration of 20 days is 2.45 miles, which would indicate that the six-mile project length should be divided into 2.45, 2.45-mile segments. But, of course this would not be practical. Using the same independent variable values used to construct Figure 3 and the following values for the other independent

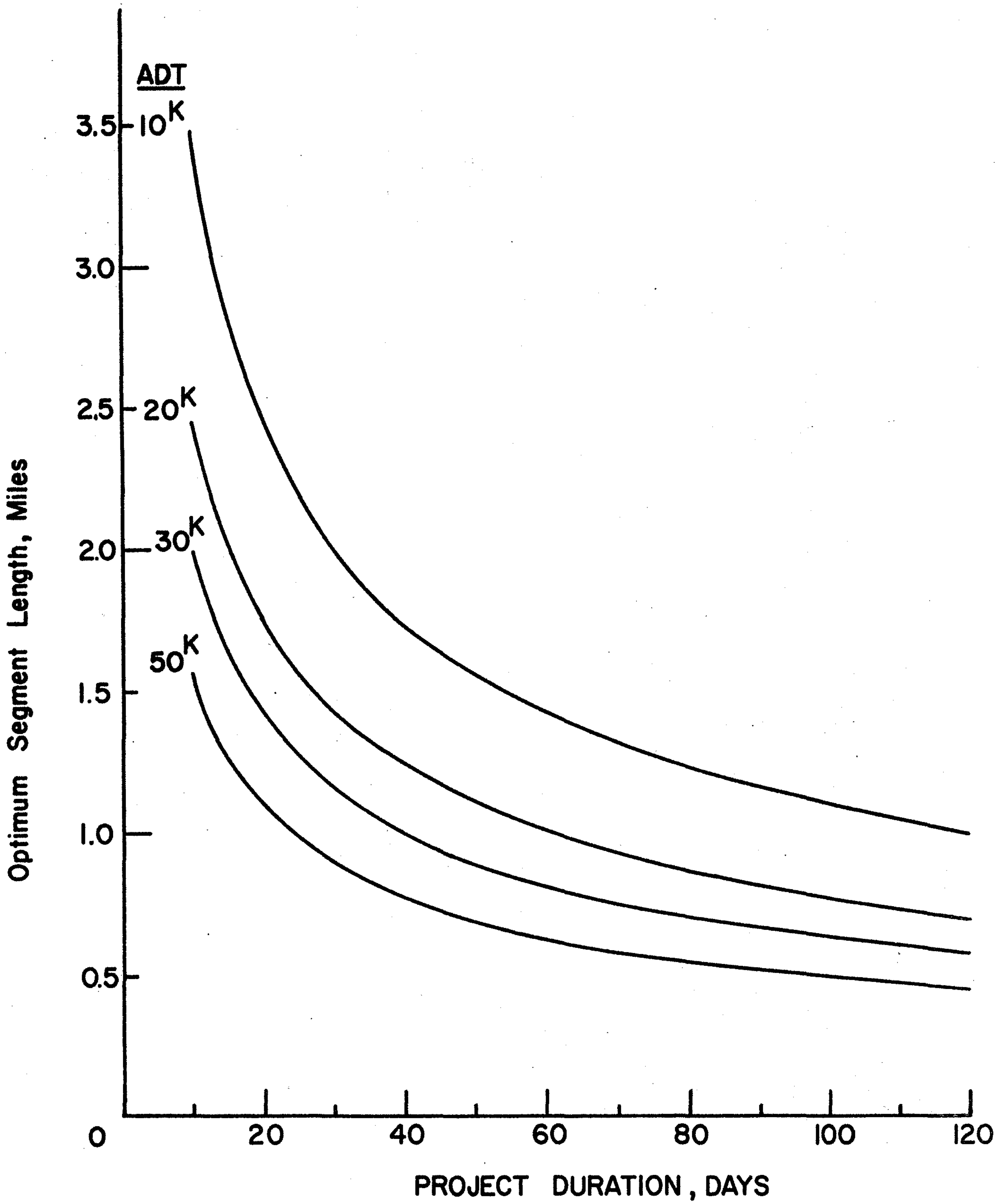


Figure 3 Optimum Segment Length vs. ADT and Project Duration for Project Length of Six Miles.

variables in Equation 13, the total project road user and traffic control costs for three, 2-mile segments and two, 3-mile segments are \$242,990 and \$242,970, respectively:

C_{ax} = \$2,600 per crossover accident,

a_x = 167.4 crossover accidents per 100 million entering vehicles,

c_{ox} = \$0.0108 per vehicle-speed-cycle change,

c_ℓ = \$10,000 per mile.

Therefore, the two, 3-mile segment plan is the practical optimum; however, the difference in total road user and traffic control costs is very small. The total road user and traffic control costs for other segment lengths are shown in Figure 4.

CONCLUSION

The optimum segment length equation derived in this study can be used in the planning and design of crossover-type traffic control in construction/maintenance zones on rural, four-lane, divided highways to determine the length of two-lane, two-way, no-passing traffic operation that will minimize the sum of road user and traffic control costs for the duration of the construction/maintenance project. Also, the equation derived for computing the sum of road user and traffic control costs enables the cost-effectiveness of crossover-type traffic control to be determined; thus, providing a basis of comparison with alternative methods of traffic control.

However, it should be noted that in the derivation of the optimum segment length equation the following key assumptions were made:

(1) Crossover and segment length accident rates are independent of segment length.

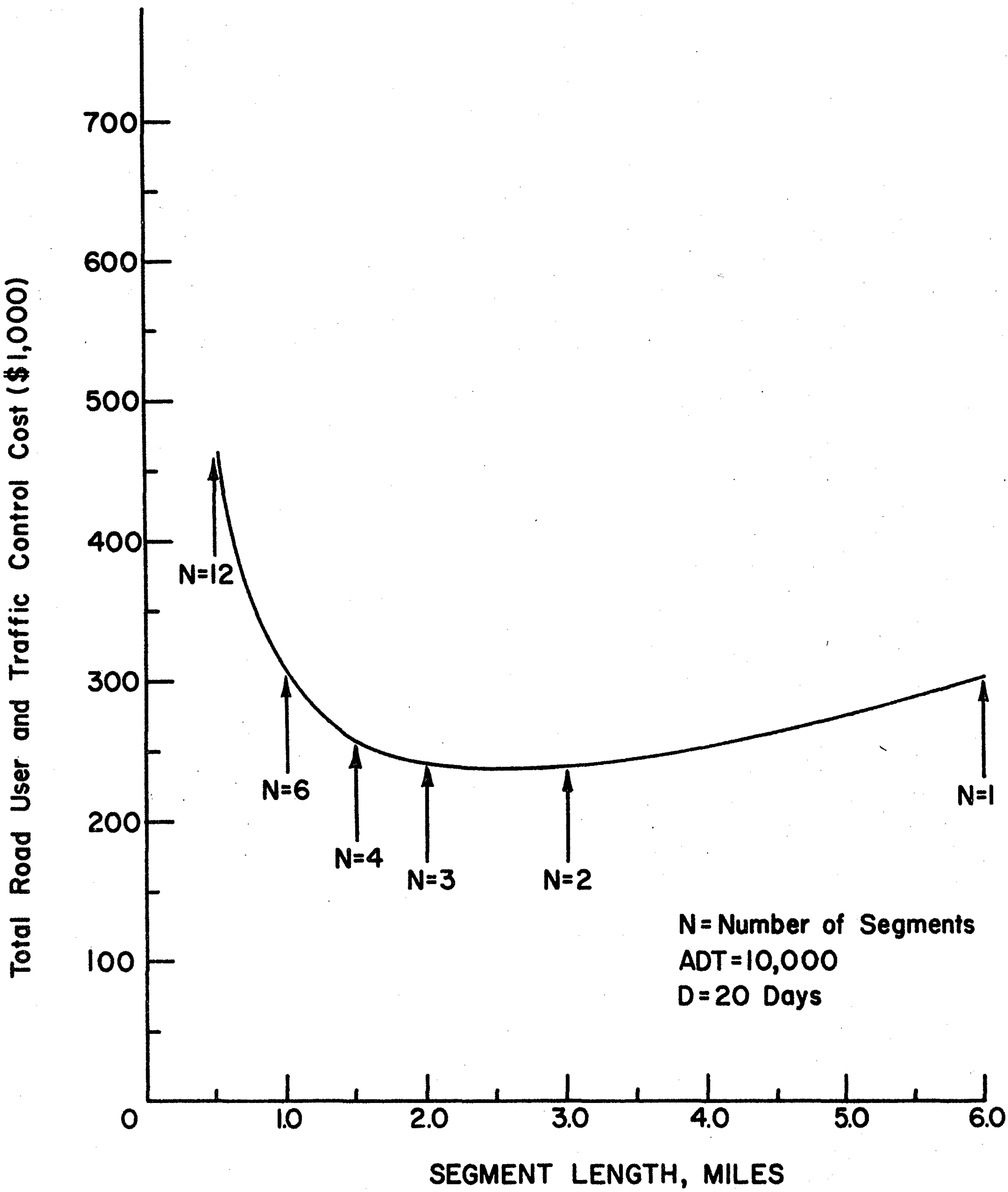


Figure 4 Total Cost vs. Segment Length for Project Length of Six Miles.

(2) Delay cost is a linear function of delay time, and in turn segment length.

(3) Unit vehicle operating costs are independent of segment length.

(4) Construction cost per crossover system and cost per mile of segment traffic control devices are independent of segment length.

If it is determined that these assumptions are not acceptable for a particular situation, then the optimum segment length equation presented here should not be used. Instead, more appropriate assumptions could be made and a new optimum segment length equation could be derived applying an approach similar to that used in this study.

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