PROGRAMMING TRANSPORT INVESTMENT: A PRIORITY-PLANNING PROCEDURE

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A priority-programming procedure was developed and is being implemented by the Ontario Ministry of Transportation and Communications. The procedure initially will deal with rural highway investment but can be extended to transit and urban areas. An earlier paper has given a general background of the procedure. This paper shows how the linear-programming formulation is a valuable extension of current methods of cost-benefit analysis. The basis of the extension is the explicit consideration of tradeoffs concerning the time of investment for improvements. The method also provides for different interest rates for discounting benefits and costs. The paper describes the linear-programming formulation including the treatment of alternatives, regional budgets, and commitments. The paper also discusses the treatment of interrelated or joint benefits of improvements. Finally, the paper presents the calculation procedure for the key benefits—user time and vehicle operating cost. This procedure accounts for variations in hourly volumes over the year and uses existing information as input.

•SELECTING transport projects for construction is a major problem for all transportation departments. Difficulties have been intensified by (a) the dramatic increase in the number of existing facilities that require ongoing maintenance expenditure; (b) the relative reduction in transport budgets because of demands for funds for education, health, and welfare; and (c) the incessant increase in the demand for transport facilities. When faced with this problem, the province of Ontario, in cooperation with Read Voorhees and Associates, Ltd., developed a methodology for priority programming for both road and transit facilities (1, 2). This methodology is being implemented. An interesting result of the development of the methodology for priorities was that the procedure also was valuable as a management tool for organizing the investment in transport facilities and providing continuity between planning studies and design and construction activities. This is described elsewhere (3). The purpose of this paper is to outline the technical aspects of the priority methodology and to indicate the flexibility of the method for handling policy variables, interdependent projects, and the like. This paper also discusses the advantages and limitations of the priority-planning technique.

PRIORITY-PLANNING PROBLEM

A transport agency generates a list of transportation improvements IMP_j's where j goes from 1 to n, the total improvements in the list. For each IMP_j certain data are calculated:

Publication of this paper sponsored by Committee on Transportation Programming, Planning, and Evaluation.

C_{jkt} = construction cost of the j th improvement incurred in year k if construction is started in the t th year. For an improvement that requires 3 years to construct, C_{jtt}, $C_{j\,t+1\,t}$, and $C_{j\,t+2\,t}$ would not be 0.

C_{jt} = present value of the construction costs of the j th improvement given construction starts in year t, all of which are discounted to year t at a specified interest rate R; that is,

$$C_{jt} = \sum_{k=t}^{k=t+p} \frac{C_{jkt}}{(1 + R)^{k-t}} \tag{1}$$

p = construction period.

t = index of year of start of construction with t = 1 usually being 2 to 4 years in the future to allow for the design of the facilities; t goes from 1 to m, and typical values of m are 20 years.

MC_{jt} = present value of the annual maintenance costs of the j th improvement for the years t through t + 25, all of which are discounted to year t at a specified interest rate R.

B_{jt} = present value of the annual benefits of the j th improvement for the years t through t + 25, all of which are discounted to year t at an interest rate R.

The data for an example improvement j are shown in Figure 1 and given in Table 1. The example takes 2 years to construct, costing $400,000 in the first year of construction and $201,000 in the second year of construction when it is started in the first year. The present value of the construction cost is calculated by using the convention that costs occurring during a year are considered to occur at the end of the year. Thus, in Table 1, the value of C_{j1}, the cost of constructing the j th project in the first year, is [$400,000 (1/1.08)] + [$201,000 $(1/1.08^2)$] or $541,800. In a similar way, C_{j2} = $543,600, and so on.

If the improvement was started in year 1, then benefits and annual maintenance costs would start to flow in year 3; benefits would be $73,000 and maintenance costs would be $20,400 in the first year of operation. These annual benefits and costs are summed over 25 years to give the values of B_{jt} and MC_{jt}. For example,

$$B_{j1} = \sum_{t=3}^{25} \frac{\text{annual benefit in year t}}{(1.08)^t} = \$752{,}800 \tag{2}$$

Similarly, if the construction was started in year t = 19, then B_{j19} would be $992,900 (Table 1). Table 1 also gives the net present value in year t of the construction of project j started in year t. This is $B_{jt} - C_{jt} - MC_{jt}$, which also is shown in Figure 1.

Each year of starting construction can be thought of as a different alternative project. To compare the alternatives of the construction of the j th project in years t = 1, . . . , x, y, z, . . . , m, one must compare the net present value for each alternative at one point in time. Normally, the common point in time is taken as the start of year 1. Thus for any 2 alternative starting dates t = x or t = y for project j we compare the present value in year 1 of $(B_{jx} - MC_{jx} - C_{jx})$ and $(B_{jy} - MC_{jy} - C_{jy})$, or we compare $[1/(1 + R)\ x - 1]\ (B_{jx} - MC_{jx} - C_{jx})$ and $[1/(1 + R)\ y - 1]\ (B_{jy} - MC - C_{jy})$ where R = discount rate. The net present value of the example project in the first years of construction t discounted to year 1 for comparison purposes is shown in Figure 1 and given in Table 1. The net present value reaches a maximum in year 12, and, with no budget constraints, this is the best time to start construction of the improvement. That is, in comparing the 20 alternatives, which are the 20 different starting dates for project j, the best alternative is that with the highest net present value in year 1. Heggie

Table 1. Values for example problem for improvement j.

Year	Input Data: 1st-Year Construction Costs	Input Data: 2nd-Year Construction Costs	Input Data: Annual Benefits	Input Data: Annual Maintenance Cost	Present Value in Year t: C_{jt}	Present Value in Year t: MC_{jt}	Present Value in Year t: B_{jt}	Net Present Value of Benefits in Construction Year t	Net Present Value of Benefits Less Costs in Year 1 for Construction in Year t
1	400,000				541,800	195,200	752,800	15,800	15,800
2	401,000	201,000			543,600	197,000	766,200	25,500	23,600
3	402,000	202,000	73,000	20,400	545,400	198,800	779,500	35,300	30,300
12									52,900
19	418,000	218,000	97,000	23,600	573,900	227,200	992,900	191,700	48,000
20	419,000	219,000	98,500	23,800	575,700	229,000	1,006,200	201,500	46,700
21	–	–	100,000	24,000				–	–
44	–	–	14,500	28,600				–	–
45	–	–	13,500	28,800				–	–

Note: All values are in dollars.

Figure 1. Example data for improvement j.

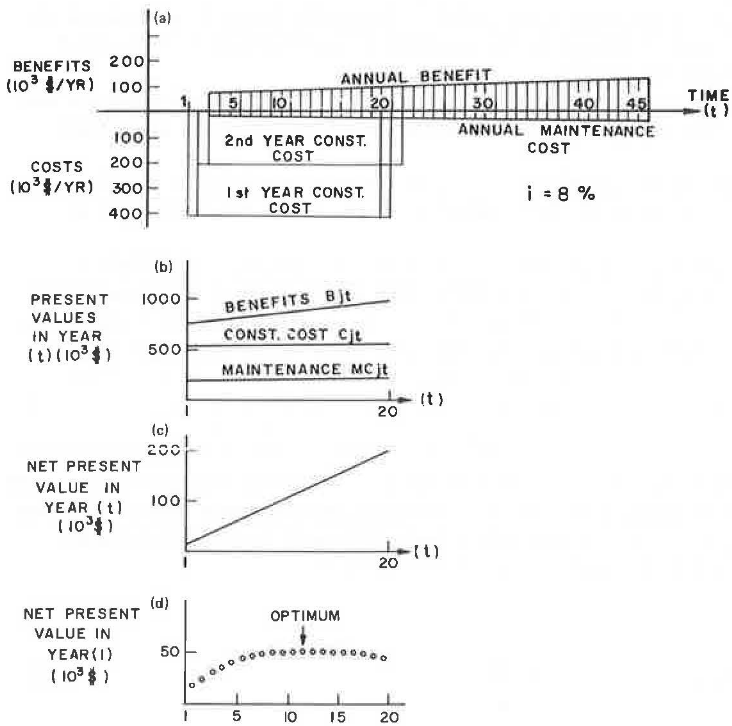
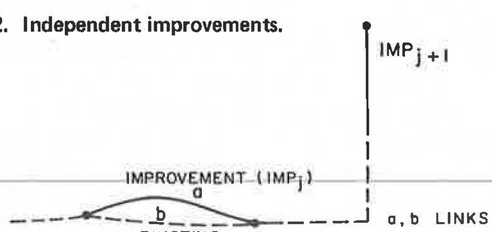


Figure 2. Independent improvements.



YEAR (t)	VOLUME ON EXISTING LINKS (b): WITH IMPj	VOLUME ON EXISTING LINKS (b): WITHOUT IMPj	VOLUME ON IMPj (LINK a)
1	3000	1,200	1,800
2	3200	1,200	2,000
⋮			
⋮			
44	8,800	1,400	7,400
45	9,100	1,400	7,700

(4) shows that, for most conditions, the maximum net present value occurs in the year when the first-year rate of return of the annual net benefits relative to the cost first exceeds the discount rate. Normally, however, the net present value criterion is easier to use. With no budget constraints, the example project would be started in year 12.

PRIORITY PLANNING WITH BUDGET CONSTRAINTS

Given a list of n improvements and their optimum construction year t_{opt}, budget constraints generally prevent starting each improvement in the optimum year. The problem then is maximizing the net present value that is due to constructing the improvements over the planning horizon m without violating budget constraints, which must be known for all m years in the planning horizon. This type of maximizing problem subject to constraints can be solved readily by linear programming (4, 8).

The linear-programming problem is to maximize

$$\sum_{j=1}^{n} \sum_{t=1}^{m} X_{jt} V_{jt} \tag{3}$$

subject to

$$\sum_{t=1}^{n} X_{jt} \leq 1 \tag{4}$$

$$\sum_{j=1}^{n} \sum_{k=t}^{k=t+p} X_{jt} CST_{jkt} \leq b_y \tag{5}$$

$$X_{jt} \geq 0 \tag{6}$$

where

X_{jt} = fraction of improvement j started in year t,
V_{jt} = present value of benefits in year t = $[1/(1 + R)^{t-1}] (B_{jt} - MC_{jt})$,
CST_{jkt} = actual construction cost incurred in year k, for a project started in year t, and
b_t = budget for year t.

Equation 3 is the maximization of benefits. We could maximize benefits less costs as was done in the example problem. However, the net benefits V_{jt} had to be maximized because the construction costs are dealt with specifically in the budget constraints. The choice of maximizing benefits means that the discount rate for comparing construction costs over time is effectively determined within the linear-programming solution and is, of course, related to the magnitude of the budget constraints. This is an advantage that becomes available with the linear-programming solution and is of course not possible with the example that had no budget constraints.

Equation 4 states that the project can be built only once and may not be built at all. If the project must be built, then this equation would be an equality. Because a non-integer linear program is used, up to m projects will not be completely started in 1 year, but, for the other n - m projects, X_{jt} will be 1.0 for some j and 0 for all other j. These so-called split projects generally are assigned to the year with the largest fraction X_{jt}, and experience has shown that this does not create difficulties.

Equation 5 is the budget constraint. The second-year construction costs for a project started in the t - 1 year will occur against the tth year budget.

Equation 6 states that construction costs cannot be recaptured by selling or "unbuilding" an improvement. Because of the linear-programming solution methods, a linear-programming problem must be expressed so that this condition holds. These constraints do not have to be explicitly stated in a linear-programming computer run because they are assumed to hold.

RESULTS OF PRIORITY PLANNING

The linear-program solution gives the following:

1. Year of start of construction for project j,
2. Present value of the net benefits of the entire priority program,
3. Discount rate for capital costs in each budget year, and
4. Measure of reduction in maximum benefits due to shifting a project from its programmed priority.

Input data are available, as a result, for further use of the method in programming improvements for design and construction. These aspects are covered elsewhere (1, 2, 3).

PLANNING HORIZON

The problem of the finite planning horizon can be managed several ways.

1. Assign a high terminal-year budget but no benefits to improvements started in year t = m the final year of the planning horizon. At the same time, change equation 4 to $\sum_{t=1}^{n} X_{jt} = 1$. The final year then becomes a dumping ground for all improvements that should not be built during the first m - 1 years of the planning horizon.
2. With the equations as given, adjust V_{jt} to reflect the fact that improvements started in the final few years of the planning horizon will not incur full construction costs. That is, if an improvement started in year t = m will incur $\frac{1}{3}$ of its construction costs in that year and $\frac{2}{3}$ subsequently, set $V_{jm} = \frac{1}{3}\,[1/(1 + R)^{m-1}]\,(B_{jm} - mC_{jm})$, which is the procedure being used in Ontario.
3. Extend the planning horizon budgets and improvement parameters far enough so that all worthwhile improvements can be scheduled.

INCLUSION OF POLICY VARIABLES

The problem of equations 3, 4, and 5 involves a simple list of improvements with only budget constraints on the construction costs. The flexibility of the linear-programming method allows many other circumstances, such as other cost constraints, regional development policies, and committed improvements, to be introduced into the priority planning.

1. Under other cost restraints, maintenance costs would be included as a cost subject to the budget. Then V_{jt} would include only B_{jt}, and CST_{jkt} would include construction and maintenance costs.
2. Under regional development policies, suppose encouraging development in northern areas of a province is desired. To do this, either (a) a special weighting

(say 1.5) can be applied to the benefits of projects in this area or (b) a separate budget constraint can be set aside for this area. For example, let X_{jta} be the fraction of an improvement j started in region a in year t, and then

$$\sum_{j=1}^{j=n} \sum_{k=t}^{k=t+p} X_{jta}\, CST_{jkta} \geq b_{ta} \tag{7}$$

This requires that at least b_{ta} be spent in the favored region in year t. This constraint also can be used to set minimum 5- or 10-year spending levels.

3. Under committed improvements, suppose an improvement j = 10 is committed for starting by year t = 7 so that it will connect with a road over a new dam being completed in year t = 9. Then we have for equation 4 for j = 10

$$\sum_{t=1}^{7} X_{10,t} = 1 \tag{8}$$

which ensures that the improvement will be started by the seventh year.

USER BENEFITS FOR INDEPENDENT IMPROVEMENTS

An improvement is independent when its benefits are independent of all other improvements considered in the planning period. Naturally, its benefits are a fraction of other road links but not of any road links subject to possible improvement. A typical independent improvement is shown in Figure 2. The benefits for improvement j do not depend on improvement j + 1 or any other improvement. This is the simplest case, and, fortunately, in intercity transport networks, most improvements are of this type. The user benefits due to improvement j in Figure 2 arise from volumes on the improvement (here assumed to be a new road) and from volumes left on the old road because of higher speeds and less congestion. An improvement is considered to be made up of a number of links that will vary in physical characteristics and volumes. In Figure 2, the improvement has only 1 link a, and the existing road is link b. The procedure developed for calculating user benefits for a particular road link involves the consideration of each hour in the year so that the speed and operating costs of the traffic can be determined more accurately. The flow chart of the user benefit calculation is shown in Figure 3. By using the permanent counting station associated with each link, one can find the distribution of hours in the year for each volume level for the annual average daily traffic for each year t. Then by using the Highway Capacity Manual (5), operating cost data (6, 7) and a value of travel time, one can calculate the total user cost on each link with and without the improvement for each hour in the year. The user benefit due to the improvement in year t then is merely the sum over the hours in the year and over the links associated with the improvement of the difference in total user costs. A computer program for Figure 3 is in operation at the Ontario Ministry of Transportation and Communications.

USER BENEFITS FOR DEPENDENT IMPROVEMENTS

Dependent improvements are defined as improvements with benefits that depend on the existence or nonexistence of another improvement. A typical situation is shown in Figure 4 in which a new intercity route is made up of 2 improvements IMP_j and IMP_{j+1}. The benefit of IMP_j and IMP_{j+1} together is greater than the sum of the benefits of each

Figure 3. Flow chart for calculating user benefits.

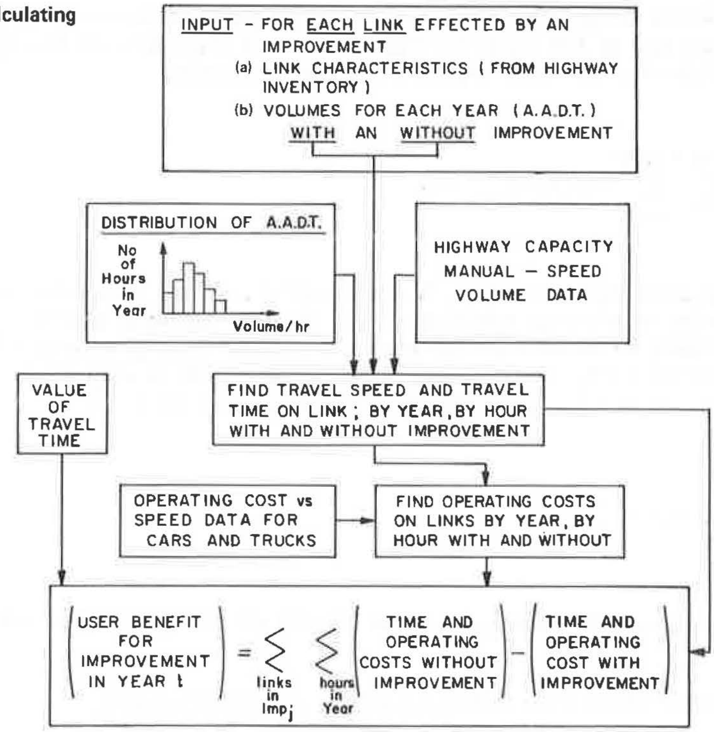
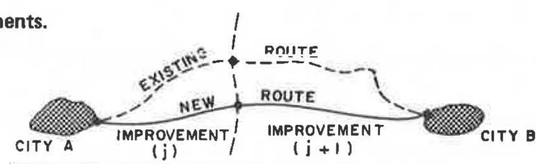


Figure 4. Dependent improvements.



YEAR (t)	PRESENT NET BENEFIT (V_{jt})			
	IMP_j ONLY	IMP_{j+1} ONLY	BOTH IMP_j AND IMP_{j+1}	DUMMY IMPROVEMENT SAY IMP_{j+2}
1	.21	.60	1.40	.59
2	.22	.62	1.45	.61
19	.30	.75	1.96	.91
20	.29	.73	1.87	.85

(ENTRIES IN $ 10^6)

individual improvement. For example, in year 2, IMP_j has a V_{jt} of $210,000 and IMP_{j+1} has a V_{jt} of $600,000. If both were started in year 2, the total V_{jt} would be $1,400,000, which is $590,000 more than the combined individual V_{jt}'s of improvement j and j + 1. This extra benefit is assigned to a dummy improvement that has 0 cost and a benefit equal to the extra benefit and can only be considered where improvements j and j + 1 are started. The constraint equations that accomplish this in the linear program are as follows:

$$\sum_{t=1}^{m} X_{jt} \le 1 \qquad (9)$$

$$\sum_{t=1}^{m} X_{j+1,t} \leq 1 \tag{10}$$

$$\sum_{t=1}^{m} X_{j+2,t} \leq 1 \tag{11}$$

$$\sum_{t=1}^{m} + X_{jt} - X_{j+2,t} \geq 0 \tag{12}$$

$$\sum_{t=1}^{m} X_{j+1,t} - X_{j+2,t} \geq 0 \tag{13}$$

$$10^{20} X_{j,1} + 10^{18} X_{j,2} + \ldots - 10^{20} X_{j+2,1} - 10^{18} X_{j+2,t} \ldots \geq 0 \tag{14}$$

$$10^{20} X_{j+1,1} + 10^{18} X_{j+1,2} + \ldots - 10^{20} X_{j+2,1} - 10^{18} X_{j+2,t} \ldots \geq 0 \tag{15}$$

Equations 9, 10, and 11 are as usual. Equations 12 and 13 ensure that no more of the dummy improvements are made than the minimum of improvement j or j + 1. Equations 14 and 15 counteract a tendency of the linear-programming solution to split the improvement (build a fraction of each over several years) to gain the dummy benefits as soon as possible. The use of descending-order-of-magnitude weights on the start of construction variables X_{jt} effectively prevents this and ensures that all improvements are built in a single year.

SEQUENTIALLY DEPENDENT IMPROVEMENTS AND STAGING

A similar technique can be used when one improvement must be constructed after another one or when an improvement must be constructed in stages. For example, the acquisition of right-of-way can be separated from the remainder of facility construction. The first stage (acquisition of right-of-way) has costs but no benefits; the second stage (facility construction) has both costs and benefits. Also stage 1 must be completed before stage 2 starts. The constraints are similar to those previously given:

$$\sum_{t=1}^{m} X_{jt} \leq 1 \tag{16}$$

$$\sum_{t=1}^{m} X_{j+1,t} \leq 1 \tag{17}$$

$$\sum_{t=1}^{m} X_{jt} - X_{j+1,t} \geq 0 \tag{18}$$

$$10^{20} X_{j,1} + 10^{19} X_{j,2} + \ldots - 10^{20} X_{j+1,2} - 10^{19} X_{j+1,2} - \ldots \geq 0 \quad (19)$$

Equations 16, 17, and 18 state that only 1 facility can be built, only 1 right-of-way can be purchased, and the amount of facility built cannot exceed the amount of right-of-way purchased. Equation 19 effectively prevents construction before right-of-way acquisition.

MUTUALLY EXCLUSIVE IMPROVEMENTS

In some circumstances other than the setting of priorities, deciding the priorities between 2 improvement alternatives [j (a) or j (b)] may be desirable. Both improvements are included in the normal way and extra constraint is added:

$$\sum_{t=1}^{n} X_{j(a)t} + X_{j(b)t} \leq 1 \quad (20)$$

This constraint states that, if a is built in some year, then b may not be built, and vice versa. Also, because of the inequality, neither need be built. A program to build a fraction f of a and a fraction 1 - f of b also would satisfy these constraints. As a practical matter, choosing to build either in the indicated year would be satisfactory.

One way that mutually exclusive improvements can occur is in alternative alignments when the primary need can be met on either alignment and not enough demand exists for 2 facilities. Also the mutually exclusive formulation is useful when different forms of a facility in the same location are to be considered. Thus the linear program can be used to decide whether a 2-lane or a 4-lane bridge should be built and, simultaneously, to determine the best construction year for the selected alternative.

OTHER BENEFITS AND COSTS

Many benefits other than user benefits are incorporated into the Ontario procedure as are costs other than construction costs. These are discussed elsewhere (2). User benefits were presented here because (a) they compose a main part of all benefits and (b) some major technical refinements were carried out in estimating these benefits as shown in Figure 3.

Salvage values of the improvements at the end of the 25-year stream of benefits normally are included in the planning procedure as a 1-time benefit. For the sake of clarity, this was not included in the examples presented here.

DISCUSSION OF RESULTS

Priority-planning techniques represent an advance over traditional cost-benefit analysis. Priority-planning techniques explicitly recognize the trade-off over time between building an improvement now or later in addition to the normal comparison of different improvements. In the testing of the technique, this advantage realized a 5 percent increase in net benefits over traditional methods of setting priorities on a year-by-year rank ordering of net present value.

Unlike other programming methods (4, 8), this technique has eliminated capital costs from the linear-programming objective function. This has the advantage that the interest rate selected is used solely for discounting benefits over time and is not also used for the discounting of capital sums. The effective discount rates for the capital sums are determined by the linear program as dual variables of the budget rows. This clear separation of discounting of benefits (mainly time saving) and opportunity cost of capital is a considerable conceptual advantage when selecting the interest rate for economic analysis.

The linear-programming technique has the advantage that commitments and other policy decisions can be inserted directly into the equations and then the technique optimizes the remainder of the improvements to be scheduled.

The main disadvantage of the procedure is the extensive data requirements. In Ontario, about 2 years is necessary to change existing data files and generate the required data. It should be noted that most of these data would be required for any economic evaluation of priorities.

The method requires the availability of a linear-programming computer program. These are generally available and did not pose any problems in tests conducted so far. The linear program uses continuous variables rather than integer variables, and this causes some splitting of projects. In the test situations and elsewhere (4), this has proved to be only a minor annoyance and has not detracted from the procedure.

However accurate and sophisticated the analysis is, the results are no better than the input data are. For this reason, work should continue on improving the accuracy of the input data in a manner similar to the refinement of the calculation of user benefits.

If an agency wishes to carry out priority programming, there appear to be considerable other managerial advantages to using the linear-programming method (3).

CONCLUSIONS

The techniques described in this paper advance economic analysis for priority programming of improvements by considering the maximization of benefits over the entire planning period given budget constraints and by clearly distinguishing between discount rate for benefits and consideration of capital costs. In the test program and in continuing application to the provincial highway system in Ontario, these techniques have shown themselves to be also practicable and useful.

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