DEMAND-DRIVEN ANALYSIS OF BOT CONTRACT DESIGN UNDER DEMAND UNCERTAINTY

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ABSTRACT

This paper aims to analyze how to determine the optimal concession period of BOT contract under demand uncertainty with the information about historical traffic demand. The previous literature about BOT contracts under demand uncertainty assumes that it is partially or fully resolved as soon as the highway is built, which may cause large estimation errors and lead to undesirable renegotiation for overlooking the demand fluctuation in the operation stage. We assumed that the growth rate of traffic demand is lognormal distributed and proposed an adaptive and dynamic prediction mechanism to predict the future traffic demand on the basis of statistical characteristics derived from the historical traffic demand, and then a decision model based on the NPV method was proposed to determine the optimal concession period with the average value and expect value of predicted traffic demand respectively. We compared the numerical results of the two types of concession periods and found that demand fluctuation in the operation stage did exist. It is more reasonable to consider the optimal BOT contract design with the expected value of future traffic demand because the risk of project failure can be quantified with probability.

Keywords: BOT contract; Concession period; Demand-driven; Demand uncertainty;

1. INTRODUCTION

With the rapid economic expansion and the booming traffic demand, a massive development of transportation infrastructures has been witnessed around the world. During the last decades, the participation of private sectors is growing in the form of BOT contract, which is a main type of public-private partnership (S. Li. et al, 2017). A private firm authorized by government takes the responsibility for building, financing and operation and it is entitled to charge tolls to road users on the purpose of covering daily expenses and making a profit during the concession period. When concession contract expires, the private firm transfer the ownership to the government. In the common international practice, the government usually sets the concession period to a fixed length (Zhang, 2009). These concession contracts usually have considerably long concession terms (often over 30 years) involving large sunk investments (Laure, 2018). However, due to the high uncertainty of future traffic demand, fixed-term concession contracts can be particularly prone to frequent renegotiation about toll adjustment and term extension, which can be disturbing and costly because contractual changes are usually undesirable (Engel, 2002).

Different sources of uncertainty or unanticipated traffic demand are likely to occur due to the considerably long concession period in a BOT highway project (Lu and Meng, 2017). C.O. Cruz (2013) mentioned that demand forecasting is one of the main sources of uncertainty in PPP projects with large sunk investments. Most previous studies that investigated the optimal BOT contract under demand certainty usually set a random variable in the demand function to show uncertainty and assume it is fully realized after the highway is built (Tan and Yang, 2012; Lu and Meng, 2017; Y. Zhang et al., 2018). Z. Feng et al. (2018) supposed that the demand uncertainty is only partially resolved and the actual realization of uncertainty is still unknown when entering into the operation stage for the lack of real operation data. A great part of demand information in operation period is largely overlooked by the previous literature and it could cause great errors in determining concession periods due to demand fluctuation during the operation period, probably caused by a newly built highway road or the unstable local economy. In other words, it is still fairly risky to determine the optimal concession term without considering the demand fluctuation in operation period. In this paper, we firstly assume that the growth rate of traffic volume is lognormal distributed and propose a demand-driven dynamic and adaptive prediction mechanism to modify the estimated traffic demand after collecting the annual newly-added operational data. And then a decision model based on NPV method is proposed to determine the optimal concession period with constant toll price and investigate the BOT contract design by considering the average value and expected value of traffic demand respectively. A case study of four real infrastructures is provided to demonstrate the application of the proposed methodology. The results show good implications for the government and private firm to design the optimal BOT contract with the information of actual traffic demand.

The remainder of this paper is organized as follows. Related literature is reviewed in Section 2. Section 3 gives the problem description and definitions of the variables. The demand-driven dynamic and adaptive prediction mechanisms and the decision models considering average value and expect value of future traffic demand respectively are studied in Section 4. We apply the models to a case study of four BOT projects in Hubei Province and some numerical results are given in Section 5. And finally, we state some concluding remarks and point out the future research directions in Section 6.

2. LITERATURE REVIEW

The determination of road capacity, toll charge and concession period has always been considered the most fundamental issue in a BOT highway contract, which are crucial for both the government and private sector. Tan et al. (2010) adopted a bi-objective programming to maximize social welfare and private profit simultaneously and analyzed the Pareto-efficient BOT contracts under perfect information on demand and cost. H. Bao et al. (2014) investigated the reasonable concession period by utilizing a bargain model with incomplete information between the government and private sector in a BOT project. X. Zhang et al. (2016) determined the optimal life span and the concession period interval jointly, where the lower boundary and upper boundary of the interval are meaningful for the private sector and the government.

Most previous literature about optimal contract design rely on the full information of traffic demand with the form of deterministic demand functions of price (F. Xiao et al., 2007; Guo and Yang, 2009; Tan et al., 2010, Tan et al., 2012a). However, it is not reasonable in most highway cases due to the demand uncertainty occurred in highway project. Tan et al. (2012b) investigated the full and partial flexibility of BOT contract under the uncertainty of future traffic demand and discussed the selection of concession period, toll level as well as road capacity with ex-post adjustments. Niu and Zhang (2013) adopted the newsvendor model and transferred the bi-objective problem into a single-objective one to study the impact of demand uncertainty on the design of the Pareto-efficient BOT contracts. They found that the economic efficiency of BOT contract will be improved with demand uncertainty. Xiao et al. (2013) modeled the impact of demand uncertainty on airport capacity choice and showed the optimal capacity choice under demand uncertainty would not change with low demand variation and high capacity cost. Lu and Meng (2017) developed a two-stage stochastic programming model to analyze the properties of optimal ETA-type contract with uncertain traffic demand and made a comparison with other two rigid contracts with fixed tolls and capacity provisions. These studies critically assumed that the demand uncertainty would be fully realized after the highway was built, not considering the effects of demand fluctuation of the project after entering into the operation period. Z. Feng et al. (2018) implicated that the demand uncertainty would be partially resolved since both the government and private sector knew which demand state they faced but were still unknown about the actual realization due to the lack of actual operation data. Tan and Tan (2014) proposed an ex-post toll adjustment procedure called Pareto-improving trial-and-error procedure (PI-TEP) for Pareto-improving BOT contracts with pre-determined road capacity and unknown demand function.

To cope with the demand uncertainty during the operation period, a number of researchers have studied the investment behavior under optimal BOT contract by modeling the demand growth and fluctuation with random process or fitting method. The key factor of determining an optimal concession period is the traffic demand occurred in the the highway project. Li and Cai (2017) adopted geometric Brownian motion (GBM) to model demand growth and fluctuation and examined the impact of government incentives on the private investment behaviors including the investment timing, capacity and price under demand uncertainty. N. Carbonara et al. (2014) assumed that the traffic volume varied stochastically in time following a geometric Brownian motion (GBM) and proposed a win-win model to calculate the concession period as the best instant of time and allowed for a risk sharing between the government and private sectors. X. Zhang et al. (2016) assumed that the cumulative distribution of traffic volume followed a sigmoidal shape following Shen and Wu (2015) and the traffic volume was a quadratic polynomial of time.

3. PROBLEM DESCRIPTION AND DEFINATION

Consider a single, risk-neutral BOT road project that has been operating for $t-1$ years with construction period T_c and concession period T_t. The firm is allowed to charge users a toll p_t in year t and the highway project receives a total traffic demand Q_t in year t while incurring the maintenance and operation costs M_t. We assume the lump-sum initial investment I occurs at the beginning of planning horizon and is sunk. The logarithmic growth rate of traffic demand in year t, β_t, is given by taking the log of growth rate, namely, $\beta_t = log(Q_t/Q_{t-1})$. And the time-depend traffic demand is formulated by

$$Q_t = Q_{t-1}e^{\beta_t} \tag{1}$$

The private firm's revenue during the concession period consists of two parts: the toll revenue that has been collected and the revenue that needs to be estimated, which totally depends on the future traffic demand. We assume that the toll remains constant in the future and the net revenue in year t is $p_{t-1}Q_{t-1}e^{\beta_t} - M_t$. And it has been widely accepted in literature that O&M costs are strongly related to traffic demand in the highway project (D. Albalate, G. Bel, 2009; Li and Cai, 2017; Y. Zhang et al., 2018). For simplicity, we assume that O&M cost is a linear function of traffic volume, namely, $M = F + \theta Q$, where F refers to the component of fixed cost and θ is the marginal operation and maintenance cost. It is worth noted that the life span of a highway project is fairly long, so the discount on the future profit or social welfare due to inflation is critical and should not be easily ignored (Niu and Zhang, 2013). The private sector's estimated net present value (NPV) during the whole concession period when the project has been operating for $(t-1)$ years can be expressed as:

$$\prod(t,\beta,T) = \sum_{j=1}^{t-1}(R_j - M_j)\delta^j + \sum_{i=t}^{T_t}(p_{t-1}Q_i - M_i)\delta^i - \alpha I \tag{2}$$

where R_j and M_j are collected revenue and Q&M costs in the past $(t-1)$ years. They are known and certain so we replace the first term of the RHS in Eq. (2) with $R(t)$. δ is the discount factor with discrete time. The procedure to determine an optimal concession period is described as follows. At phase I, we use the historical data of traffic demand to compute the value of growth rate to estimate future demand with the proposed demand-driven dynamic prediction and adaptive mechanism. And at phase II, after the future traffic demand is estimated, a decision model by NPV method is developed to obtain the optimal concession period when the private firm reaches its requested level of profit.

4. ANALYSIS OF TWO TYPES OF BOT CONTRACTS

In this section, we study two different types of BOT contracts and discuss the optimal BOT contract design based on the growth rate. The two types of contracts are called FTa-type contract and FTe-type contract (Athias and Saussier, 2007; Lu and Meng, 2017). Specifically, FTa-type contract refers the BOT contract where the government (or private firms) makes an optimal decision on contract design based on the average value of random traffic demand while FTe-type contract is based on the stochastic distribution of random traffic demand (Lu and Meng, 2017). In our model, the randomness of traffic demand is mainly reflected on the uncertainty of the growth rate β_t . The toll charge assumes to remain constant during the whole concession period, which is consistent with the situation in real life. The demand distribution of the growth rate could give us a robust numerical interval of the concession period and the average value of traffic demand is often used to represent uncertainty since it is usually easy to compute and relatively accurate to predict the future demand.

4.1 Model analysis of FTa-type BOT contract design

In this section, we will analyze and discuss the model formulation of the FTa-type BOT contract design under demand uncertainty. The logarithmic growth rate β is assumed to normal distributed and we set the estimated logarithmic growth rate as the average value of historical logarithmic growth rate, denoted by μ_t, according to the definition of FTa-type contract. The the total estimated NPV under FTa-type contract is:

$$\prod^{a}(t, \mu_t, T_a) = P(t) + \sum_{i=t}^{T_a}(p_{t-1}\bar{Q}_i - M_i)\delta^i - \alpha I \tag{3}$$

where $P(t)$ is the collected profit and it only relies on the time t. T_a is the optimal concession period under FTa-type contract. $\bar{Q}_i$ is the average traffic demand in future concession period in year t, which can be defined as:

$$\bar{Q}_t = Q_{t-1}e^{\mu_t} \tag{4}$$

where μ_t is the average growth rate before year t and $\mu_t = (\beta_2 + \beta_3 + \ldots + \beta_{t-1})/(t-2)$. According to Eq. (4), we can obtain the estimated traffic demand after year t based on Q_{t-1} and μ_t, for instance, $\bar{Q}_{t+k} = Q_{t-1}e^{(k+1)\mu_t}$. Therefore, we can rewrite Eq. (3) as:

$$\prod^{a}(t, \mu_t, T_a) = P(t) + \sum_{i=t}^{T_a}(p_{t-1}Q_{t-1}e^{(i-t+1)\mu_t} - M_i)\delta^i - \alpha I \tag{5}$$

And then, we define the gap between total estimated NPV and requested profit level and it can be expressed as:

$$G(t, \mu_t, T_a) = max\left\{R - \prod^{a}(t, \mu_t, T_a), 0\right\} \tag{6}$$

where R is the requested profit level of the private firm, namely, $R = \alpha\phi I$, and ϕ is the required rate of return. Suppose that the road project has a maximum duration of operation period denoted as T_m, which means that the concession term of the project cannot be extended more than T_m. In Chile, the Concession Law establishes a maximum duration of 50 years (Vassallo, 2006). According to the regulations of BOT project implemented since 2014 in China, the maximum duration is usually 25 or 30 years. However, this regulation has a problem that if the realized revenue of the firm is still lower than the requested one when the contract expires at T_m , the concessionaire will face a high risk of project failure, even not be able to recover its investment. In that case, a decision model can be established by minimizing the gap $G(t, \beta . T)$, which can be expressed as:

$$\textbf{Min} \quad G(t, \mu_t, T_a) = max\left\{R - \prod^{a}(t, \mu_t, T_a), 0\right\} \tag{7}$$

$$\textbf{s.t.} \quad T_a = inf\left\{x \le T_m : \prod^{a}(t, \mu_t, x) \ge R\right\} \tag{8}$$

the NPV in Eq. (5) is monotonically increasing with time t within the optimal concession period, which means that the private sector is willing to end its operation when its NPV reaches the maximum (X. Zhang et al., 2016). Therefore, the gap $G(t, \mu_t, T_a)$ is monotonically decreasing with time t so we can directly obtain the optimal T_a by bisection method. Eq. (8) shows the principle that the concession period will end when the firm has received its requested NPV from the users. Maximum duration constraint is also mentioned in Eq. (8).

4.2 Model analysis of FTe-type BOT contract design

In this section, we will analyze and discuss the model formulation of the FTe-type BOT contract design under demand uncertainty. Different from Section 4.1, we consider β_t as a stochastic variable that is independent identically distributed following a normal distribution in the future operation period with the mean μ_t and standard deviation σ_t, namely, $\beta_t \sim N(\mu_t, \sigma_t)$. The the total estimated NPV under FTe-type contract can be expressed as:

$$\prod^{e}(t,\beta,T_e) = P(t) + \sum_{i=t}^{T_e}(p_{t-1}\hat{Q}_i - M_i)\delta^i - \alpha I(y) \tag{9}$$

Where T_e is the optimal concession period under FTe-type contract and $\hat{Q}_i$ is the expected traffic demand in year t and it can be expressed as:

$$\hat{Q}_t = Q_{t-1}e^{\beta_i} \tag{10}$$

we rewrite Eq. (9) as:

$$\prod^{e}(t,\beta,T_e) = P(t) + \sum_{i=t}^{T_e}[(p_{t-1} - \hat{\theta}_t)Q_{t-1}e^{\sum_{k=t}^{i}\beta_k} - \hat{F}_t)]\delta^i - \alpha I(y) \tag{11}$$

Regard $e^{\sum_{k=t}^{i}\beta_k}$ as a random variable, denoted by $B(i)$, and we set Γ_j as the sum of random variable with normal distribution, which can be defined as:

$$\Gamma_j = \prod_{t=1}^{j}\gamma_t = e^{\sum_{i=1}^{j}\beta_i} = e^{\beta_1+\beta_2+\ldots+\beta_j} \sim logN(e^{j\mu+j\sigma^2/2}, (e^{j\sigma^2}-1)e^{2j\mu+j\sigma^2}) \tag{12}$$

According to Eq. (12), the expected value as well as variance of $\prod^{e}(t,\beta,T_e)$ is given by:

$$E\prod^{e}(t,\beta,T_e) = R(t) + (p_{t-1} - \hat{\theta}_t)Q_{t-1}\sum_{i=t}^{T_e}(e^{(i-t+1)u_t+(i-t+1)\sigma_t^2/2} - \hat{F}_t)\delta^i - \alpha I \tag{13}$$

$$V\prod^{e}(t,\beta,T_e) = [(p_{t-1} - \hat{\theta}_t)Q_{t-1}]^2\sum_{i=t}^{T_e}(e^{(i-t+1)\sigma_t^2} - 1)e^{2(i-t+1)\mu_t+(i-t+1)\sigma_t^2}(\delta^i)^2 \tag{14}$$

According to Eq. (11)-(14), we can determine a robust concession period with a modified decision model based on program (7)-(8). The modified decision model can be expressed as:

$$\textbf{Min} \quad G_e(t,\beta,T_e) = max\left\{R - \prod_{1-\varepsilon}^{e}(t,\beta,T_e), 0\right\} \tag{15}$$

$$\textbf{s.t.} \quad T_e = inf\left\{x \le T_m : P(\prod^{e}(t,\beta,X) > R) \ge \varepsilon\right\} \tag{16}$$

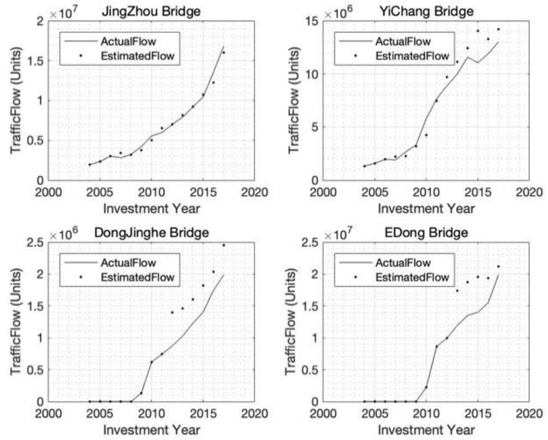
Where the lower quantile of the expected NPV where the probability value equals to $1-\varepsilon$ showed in Eq. (15) can be expressed as:

$$P(\prod^{e}(t,\beta,T_e) > \prod_{1-\varepsilon}^{e}(t,\beta,T_e)) = \varepsilon \tag{17}$$

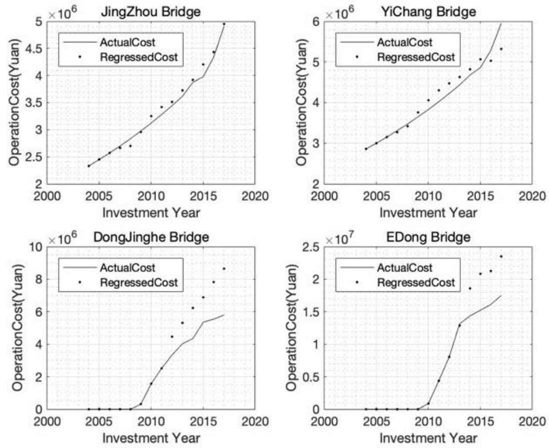
It is proved that the expected NPV in Eq. (18) is log-normal distributed. Therefore, the mean value of expected NPV is able to represented as a function of T_e, denoted by $\mu(t,T_e)$, as well as the standard deviation $\sigma(t,T_e)$. We can determine the robust concession period based on the culminative density function of lognormal distribution $\Phi_{log}(\cdot)$ with the corresponding mean value $\mu(t,T_e)$ and standard deviation $\sigma(t,T_e)$.

5. RESULTS

In this section, we applied the proposed methodology to the case of the toll bridge projects in Hubei Province, since the collected data of traffic demand on bridge is closer to the actual demand and users pay the toll fee per vehicle when they drive across the bridge, not like other motorway projects where the toll is related to not only the traffic volume but also the kilometers users drive on the road, which are imprecise because the length of each vehicle drives on the highway road is different and hard to measure. Actual data of the four toll bridge projects from 2004 to 2017 is adopted in this section. The yearly traffic demand has been transformed into passenger car units, considering different types of vehicles. The projects were established in different years and have been operating for some time. They have the same toll level and ex-ante concession period, which are 15 yuan/vehicle and 30 years respectively.



(a) Estimated traffic demand and actual demand



(b) Estimated cost and actual cost

Figure 1. Estimated traffic demand and operation cost

5.1 Estimated traffic demand and operation cost

This section presents a comparison between the estimated traffic demand and the actual one under FTa-type BOT contract to show the numerical results of demand forecast with our dynamic and adaptive prediction mechanism. The estimated operation cost is able to be obtained based on the estimated traffic demand by the linear regression model. It is found from Fig. 1(a) that error between the predicted demand and actual demand of JingZhou Bridge and YiChang Bridge is obviously smaller than the remaining projects with MAPE computed as 6.64% and 12.76%, which is lower than that of DongJinhe Bridge and EDong bridge computed as 22.53% and 19.39%. Larger amount of valid data is fairly benefit for making more accurate predictions since there are more real data of traffic demand being used to obtain predicted traffic volume. As Fig. 1 depicts, we found a positive correlation between annual traffic demand and corresponding operational cost.

5.2 Optimal concession period under two types of contracts

In this section, we compared the optimal concession periods under the two types of BOT contracts with regulated concession term. The parameter of probability that the franchise holder could reach its level of expected profit ε is set to be 0.95. The discount rate r and requested rate of return ϕ are 10% and 10% as the previous section. From figure. 3 we can find that the length of concession period is unstable in the first few years and appears to stabilize with the operation of the BOT project, which is mainly caused by the demand fluctuation in the operation phase. Besides, some of the projects show an increasing trend of concession period. We believe that the competence with other transportation facilities is related with this phenomenon, such as a newly built highway road near the bridge, which will be investigated in further study. The concession periods of FTe-type contract are generally larger than that of FTa-type periods. Compared with the FTa-type concession period, it is less risky to consider the optimal concession period under FTe-type concession contracts. Table 1 shows the computed robust concession terms in 2017 with different value of probability. The longer the concession period is, the larger the probability value turns out to be. The ex-ante concession term determined by the government and the private firm is 30 years, and we can evaluate the risk of project failure when the contract expires based on the numerical results of computed robust terms.

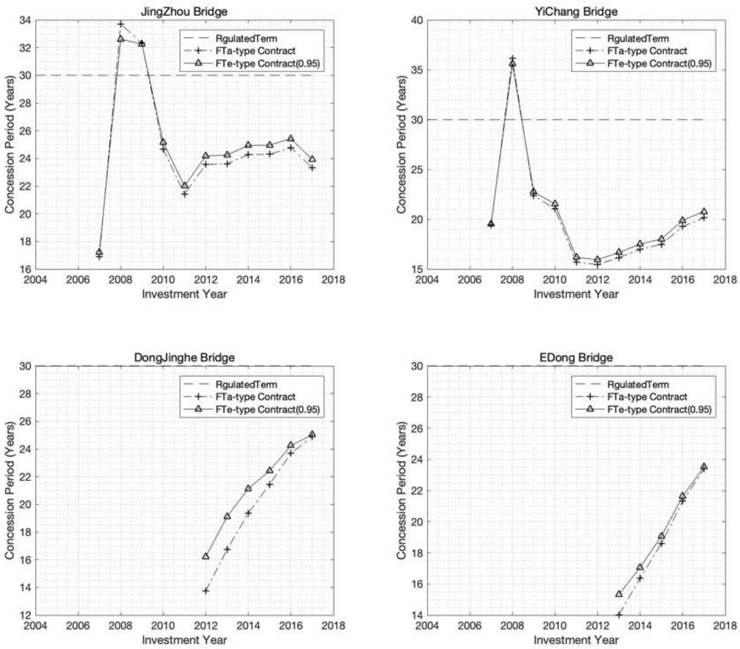


Figure 2. Comparison of FTa-type and FTe-type contracts

6. CONCLUSIONS

A key factor of a toll road project is the agreement on the length of concession period. In this study, we mainly studied the optimal concession term under two types of BOT contract, namely, FTa-type contract and FTe-type contract. A case study of four main toll bridge projects in Hubei province is studied based on the actual data generated during the operation stage. We assume that the growth rate of traffic demand is lognormal distributed and regard it as a reflection of demand uncertainty. It is found that the computed concession term is unstable in the first few years and gradually stabilize at a relatively reasonable level, which indicates that the demand fluctuation during the operation stage does exist and cannot be ignored. And the increasing trend of concession term may derive from the competition with other similar facilities, such as a newly-built railway station or motorways. The numerical results of the two contracts show that the longer concession term is, the less risk of project failure the private sector assumes. Compared with the FTa-type concession period, it is less risky to consider the optimal concession period under FTe-type concession contracts.

Table 1. Robust concession terms computed in 2017

Bridge Project	Robust term	Probability value	Robust term	Probability value	Robust term	Probability value
Jingzhou Bridge	23.77	0.90	23.93	0.95	24.21	0.99
YiChang Bridge	20.61	0.90	20.78	0.95	21.12	0.99
DongJinhe Bridge	24.17	0.90	25.03	0.95	28.36	0.99
EDong Bridge	22.82	0.90	23.51	0.95	25.82	0.99

There are some avenues for future studies. First, we assume that the toll price remains constant in the future operation period and consider the traffic demand as totally exogenous. It is more challenging to assume that the traffic demand is endogenously determine by toll price and road capacity and investigate the multiple period dynamic problem of optimal contract design under demand uncertainty by stochastic process like GBM or Markov process. Second, we suppose that the increasing trend of optimal concession period may derive from the surrounding transportation facilities and it is of great value to study the impact of a new entrant's uncertain entry to the old BOT project in a road network.

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