

Article

External Benefit Assessment of Urban Utility Tunnels Based on Sustainable Development

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Abstract: Urban utility tunnels (UUTs) can have great external benefits in terms of social and environmental aspects for the sustainable development of a city. However, the high initial construction cost has been the main obstacle to the promotion of UUT projects for a long time. Although several evaluation methods for the benefits of UUTs have been proposed, most of them focus on the cost assessment during the construction period and are limited in terms of their scientificity, the feasibility of the valuation methodology and the comprehensiveness of external categories. The external benefit assessment of UUTs during their service life remains lacking, leading to an incomplete insight into UUT projects. Therefore, a scientific evaluation method of the long-term external benefits of UUTs is still needed from the perspective of urban sustainable development. This paper proposes a composite market price method to carry out a simple but systematic evaluation of the positive externalities of UUTs in monetary terms. Detailed instructions on the operation of the method are also elucidated to further improve its practicability. The feasibility and validity of the method is then demonstrated through a case study of the UUT project in Xiong'an New Area, China. It is also concluded that UUTs can benefit all social subjects and that a classification of externalities based on different social subjects can foster better development and broader support for the implementation of UUTs.

Keywords: urban utility tunnels; external benefit assessment; monetary valuation; the composite market price method; urban sustainable development



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1. Introduction

Urban utility tunnels (UUTs) have been gradually adopted as a sustainable solution for providing municipal services since the late 19th century [1]. Different urban pipelines can be integrated together in an easily accessible tunnel space to replace traditional overhead transmission lines or trench opening systems as shown in Figure 1 [2]. People can routinely maintain or renovate utilities inside the tunnel without interfering with the normal traffic and environment on the ground. Therefore, pipeline failures can be dramatically decreased, which means a longer asset life and fewer maintenance costs [3]. Due to fast urbanization and outdated planning, utilities can be interlaced with each other under roads, leading to the complicated “spaghetti subsurface problem” and hindering further development [4,5]; by means of UUTs, this annoying problem can be effectively resolved, and extra subsurface space will be saved for other underground facilities in the future [6–8]. However, these are the external benefits of UUTs which originally do not result in actual income.

On the other hand, adopting UUTs could increase total investment by approximately 50% in comparison with traditional utility construction methods [9]. Stakeholders usually emphasize the financial analysis, which only calculates the actual expenses and incomes of the project entity in real markets (e.g., annual rental and maintenance fees from utility companies) [10]. Such a huge initial investment usually means that it is difficult for UUT projects to gain approval by the local authority or private sectors. The reality turns out to

be that most of the implemented UUT projects are in new urban areas [11]. Although the demand for UUTs in old districts is no less than in new urban areas, their development is always obstructed by the increased technical and financial issues. Besides, the implemented UUTs are sometimes left idle, with pipeline companies refusing to take part in and pay for their development.

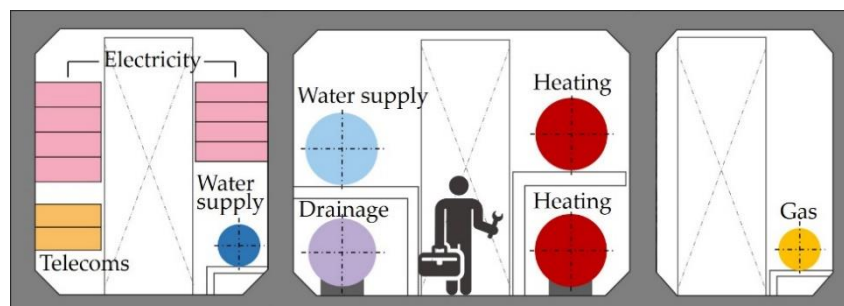


Figure 1. Typical layout of an urban utility tunnel (UUT).

It is unfair and unsustainable to make judgements only according to the internal cash flows of a project but to neglect its positive externalities for the urban environment and society as a whole in the long term. Since the real market price can hardly reflect the true social and environmental worth of UUTs, previous research works have been done to propose various methods for evaluating the externalities of UUTs [12–18]. Specifically, most of these works have been based on comprehensive cost comparisons between UUTs and directly buried pipelines, due to the reality that, normally, either one—but not both—would be adopted. The results verified the better cost performance for UUTs, which promoted the utilization of UUTs to a degree. However, some of the evaluation frameworks focused solely on the differences related to the construction technologies between UUTs constructed with trenchless technology and traditional open-cut utilities but neglected the evaluation of UUTs during their service life. Some only intended to put forward instructional conclusions and dramatically simplified the calculation process, with little reference significance. The others, built externality factor systems but paid insufficient attention to the scientific selection of valuation methods, which greatly decreased the validity of the valuation frameworks. A more scientific, feasible and referential method with previously neglected externality categories is still needed to better reveal the sustainability of UUTs. Meanwhile, with the increasing acceptance and implementation of UUT projects [19,20], their external benefit assessment requires more study to further show the advantages of utilizing UUTs and assist in the subsequent allocation of social and environmental resources. Therefore, it is crucial to undertake a further analysis and evaluation of the long-term external benefits of UUTs in monetary terms.

In this paper, we intend to provide an overall view of the sustainability aspects of utilizing UUTs by proposing a comprehensive but simple method for the external benefit assessment of UUTs in monetary terms, which can also serve as a persuasive proof during planning and policy making. In Section 2, a literature review of the external benefits of UUTs and their valuation methods is presented. Then, an external benefit assessment method of UUTs based on a combination of market price-based approaches is introduced in Section 3. A detailed analysis and explanation of the valuation method adoption, parameter selection and the criteria used for each external benefit are provided separately. The method is therefore feasible and referential for both old districts and new urban areas with insufficient data. Subsequently, the proposed method is applied to a case study of the UUT project in Xiong'an New Area, China in Section 4 to justify its feasibility and validity. Based on the valuation results of the case study, characteristics of the external benefits of the UUT as well as their impacts on resource allocation are then discussed. Conclusions are finally drawn in Section 5.

2. Literature Review

2.1. External Benefits of UUTs

Externalities refer to the benefits and costs that are not received or borne in financial terms by a product or service itself, but are reflected by the contributions or harm to a third party outside of the context of the market.

Initially, the term “social costs/benefits” was considered to be the same as external costs/benefits. Gilchrist and Allouche [21] built a social cost indicator system by subclassifying the social costs of construction into four categories; i.e., traffic-associated, economic activities-associated, pollution-associated (e.g., noise, dust and vibration) and ecological/social/health impacts (e.g., damage to recreational facilities). Ormsby [17] regrouped those categories and divided the total external costs into social costs, environmental costs and economic costs, where social costs refer to traffic-associated costs and impacts on health, environmental costs refer to impacts on environment and ecology and economic costs refer to economic activities-associated costs (e.g., lost business income). Most other studies, however, regarded external economic costs as part of social costs and suggested that external values/costs were the summation of social values/costs and environmental values/costs [12,16]. In addition, Hunt et al. [12,22,23] listed the direct economic costs, indirect economic costs, social costs and environmental costs of UUTs within a timeline framework which was divided into the pre-construction stage, construction stage and post-construction stage. The rest of the studies that have taken the externalities of infrastructure construction into account have mainly built their factor systems using the externality categories that are common in most utility construction projects and are suitable for quantitative evaluation [24].

The social benefits of UUTs can be regarded as averting the damage or inconvenience to the public (i.e., social costs) possibly caused by traditional overhead cables or directly buried pipelines [16]. According to previous studies [12,17,21,25,26], the social costs that are mostly incurred include travel delays, vehicle operating costs, pavement damage, local business losses, parking losses, accidental injury and death and property loss. Specifically, by employing UUTs, the future installation and rehabilitation of pipelines can be finished without extra road excavations [3,27], thus eliminating huge traffic delay costs, which ordinarily have accounted for 50% of the total social costs of trench opening systems [26]. The pavement damage, local business loss, parking space loss and worker safety problems incurred by excavations in the road can also be greatly reduced [2,3,12,16,28]. Additionally, the tunnel structures and monitoring systems of UUTs prevent pipe burst accidents from hurting pedestrians on the road. The disaster prevention ability of the utilities inside UUTs are also enhanced during destructive weather, seismic events and, even, air raids [29,30]. More fundamentally, UUTs could save shallow subsurface space resources by their more compact urban underground space (UUS) utilization, which was usually neglected by the public in spite of its high economic value [29,31,32].

The most commonly included categories of environmental costs associated with infrastructure construction are air, dust and noise pollution, environmental damage and contamination and root damage. [12,17,25,26]. The use of UUTs avoids the noise, dust and dirt pollution generated by aboveground construction sites in the case of the maintenance of directly buried pipelines [24]. Obtrusive overhead cables also disappear after the implementation of UUTs, protecting the local landscape with high visual benefits [33,34]. Besides this, Hunt et al. (2014) and Jung et al. (2007) [12,16] suggested that people should also include the loss of habitat, root damage and land defacement caused by excavations in the comparison between UUTs and traditional utilities. However, monetary evaluation methods for these benefits have not been proposed. Additionally, a decrease of the resource wastage (e.g., wastage of water and natural gas) caused by pipeline leakage should also be mentioned as a long-term external benefit of UUTs.

2.2. Economic Valuation Methods

Regarding the internal costs and benefits of underground municipal infrastructure, the real market prices of construction and operation can be directly calculated and employed. Nevertheless, the externalities of these underground facilities are rather complex and difficult to quantify [12,16]. Different types of valuation methods are shown in Figure 2 [30,35,36].

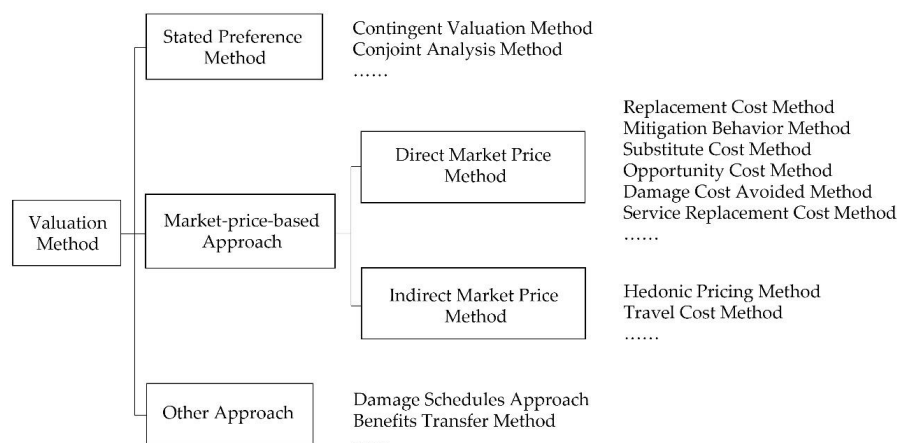


Figure 2. Valuation methods for external benefits.

Stated preference (SP) methods are also known as non-market valuation methods that calculate the public willingness to pay (WTP) for certain goods or services based on the responses of carefully surveyed respondents. For example, in terms of removing construction noise, SP methods such as the contingent valuation method (CVM) investigate the exact price that citizens are willing to pay to avoid the noise [33]. SP methods have the advantage of enabling researchers to assess the total value of non-market goods, including their passive use value [37].

Market price-based approaches, as the name suggests, use the associated market prices to value non-market goods. They are useful when public WTP is difficult to measure [26,31]. These approaches can be further categorized into direct market price methods and indirect market price methods. Direct market price methods indicate the value of non-market goods directly with the accessible market prices of goods or services that can be taken as the replacement measures, or the mitigation measures, etc. Many of the commonly used methods are of this type, such as the replacement cost method, the mitigation behavior method, the substitute cost method, the opportunity cost method and the damage cost-avoided method. The replacement cost method uses the cost of recovering from damage to represent the value of existing goods; for example, using the treatment fee to indicate the value of soil conservation [38]. The mitigation behavior method, in contrast to the replacement cost method, evaluates the mitigation strategies that reduce the loss induced by damage; for example, by replacing distribution poles that have reached the threshold criteria for strength to reduce existing vulnerability in the face of wind storms [39]. By adopting the substitute cost method, values of non-market goods such as groundwater over-pumping reduction (one of the benefits provided by China's South-to-North Water Diversion Project) can be estimated based on the market price of substitutes such as the remediation cost for groundwater pollution [40]. The opportunity cost method provides a valuation of projects or goods through the opportunity cost; for example, the foregone income when changing the goals of land use from making the most profit to a sustainable project [41]. Relatively speaking, the damage cost-avoided method is more conservative, since it adopts the basic value of the protected property rather than the maximized value that the property can produce. Furthermore, methods combining the use of those market price-based approaches together with other valuation methods are being developed con-

tinuously for certain study conditions; for example, the service replacement cost method (SRCM) combines the replacement cost method, the substitute cost method, and to evaluate the externalities of underground rail transit or the UUS as a whole [30,42].

Indirect market price methods, also known as revealed preference methods, calculate the public preference for certain goods or services from the public behavior shown in existing markets indirectly. For example, the hedonic pricing method, a kind of revealed preference methods, uses the declination of housing price caused by noise pollution to determine its social costs [16,43].

In addition, there are still other basic valuation methods that are suitable for counting external benefits, each having their own advantages compared with the two types of approaches listed above. For example, non-monetary methods such as the damage schedules approach (also called the pairwise comparison approach) provide a valuation of various items or goods in relative terms, avoiding the undependability and inconsistency of fixing exact prices [44,45]; additionally, the benefits transfer method basically functions by generalizing and adapting information and patterns from existing research or practices, which can be very useful for developing countries [46,47].

Most of the previous studies evaluating the externalities of UUTs have made combined use of SP methods and market price-based approaches or have not focused on the scientific selection of valuation methods. It should be noted that since SP methods investigate the comprehensive total value of non-market goods, the combined use of them and other market price-based methods can result in a large amount of double-counting and a consequent unreliability when comparing between and adding these values. Additionally, the comprehensiveness of externality categories and feasibility of evaluation methods in previous studies have also been limited. The situation calls for a more scientific, feasible and referential method with previously neglected externality categories. In addition to the simple comparison between the total costs of UUTs and directly buried pipelines, more detailed and advanced information is also required for the progressing development stage of UUT utilization, contributing to urban sustainable development by supporting decision making and optimizing resource allocation.

3. Methodology

3.1. The Composite Market Price Method

Each valuation method of externality has its advantages and limitations and is suitable for different objects. It is crucial to adopt the most appropriate methods during the assessment. As stated above, it is not scientific to make mixed use of SP methods and market price-based approaches. Meanwhile, although using SP methods can reveal the total value of non-market goods with the passive use value included, presenting different types of values as a whole is unlikely to help in the fine optimization of resource allocation. In addition, survey results are less likely to be approved by the private sector than the conservative monetary valuations with market prices, as the private sector is profit-oriented. Therefore, a composite market price method is proposed in this paper that evaluates each external benefit of UUTs mainly with the suitable market price-based approach which depends on whether the damage or loss can be directly valued or should be indirectly valued through the replacement cost or substitutes.

Since directly buried pipelines are bound to be built if a UUT is not adopted, it is still scientific and effective to assess the external benefits of UUTs in comparison to directly buried pipelines. Based on such a comparison, there must be damage avoidance (such as reducing the wastage of resources due to pipeline leakage) and resource replacement (such as the extra construction cost for pavement due to its service life loss caused by repeated excavations, which is no longer needed with the implementation of UUTs), providing appropriate conditions for the adoption of market price-based approaches. Besides, although market price-based approaches using the prices of market goods to represent the external values of non-market goods and omitting their passive use values are unable to provide precise total economic values, the base assumption of this type of

approach that the projects or goods must be worth at least the cost that people have to pay without them is sufficient to provide a conservative estimate and to illustrate a general contour of external benefits.

This research mainly focuses on the long-term benefits during the service life of UUTs. The benefit factor system (as shown in Table 1) is built based on the acknowledged advantages of UUTs over directly buried pipelines, which are as follows [9,12,29,48]:

1. Rational and integrated land use;
2. The clearer state of the location and performance of UUT structure and pipelines inside it;
3. Improved reliability of municipal services (due to better inspection methods and quicker treatment with the adoption of a monitoring system);
4. Capability to be operated, maintained and repaired from the inside (i.e., this eradicates the need for repeated excavation and reinstatement (E&R) procedures);
5. Closeness, preventing a mutual influence between the inside and outside of the structure;
6. Structural reliability against outside force;
7. Improvement of the urban environment.

Table 1. Valuation methods of the long-term external benefits of UUTs.

External Benefits	Explanation	Valuation Methods
Conserving urban land and underground space	Reduction in underground space occupation by integrating pipelines and cables in the tunnel	Damage cost-avoided method
Reducing the wastage of resources	Reduction in pipeline leakages by avoiding excavation or other outside force damage and initiating timely treatments	Damage cost-avoided method
Avoiding disruption to local business	Avoidance of business loss caused by aboveground maintenance in the vicinity	Damage cost-avoided method (+ Benefits transfer method)
Avoiding traffic delays	Avoidance of vehicle and pedestrian traffic interruption caused by aboveground maintenance	Damage cost-avoided method + Replacement cost method + Stated preference method/Benefits transfer method
Conserving the service life of pavement	Avoidance of service life loss caused by repeated excavations	Replacement cost method
Conserving aboveground public space	Avoidance of taking up roadside parking spaces	Damage cost-avoided method + Substitute cost method
Reducing serious accidents of urban pipelines	Reduction in huge loss of public property and human life induced by serious accidents due to nearby construction damage	Damage cost-avoided method + Human capital approaches
Enhancing urban resistance against natural disasters	Sheltering municipal pipelines and reducing indirect loss caused by failures in lifeline projects	Replacement cost method + Substitute cost method + Damage cost-avoided method/Benefits transfer method
Avoiding dust, noise and visual pollution	Avoidance of dust and noise caused by aboveground maintenance and visual intrusion brought by aerial cables and construction sites	Stated preference method

The integrated arrangement of pipelines and cables in the UUT construction saves space both aboveground and underground. The clearer state of UUT construction largely reduces the possibility of infrastructure damage caused by nearby construction or other unexpected outside forces. Further, the clearer state of pipelines inside UUTs and their improved reliability greatly reduce the occurrences and consequence of pipeline failures, which usually result in resource leakage and serious accidents (especially in the case of gas pipe failures). Additionally, the pipeline failures that are not prevented and the destruction they might cause are separated from the aboveground urban life by the structure of UUTs.

With the capability of being operated, maintained and repaired from the inside, UUTs need few construction works that involve the E&R of the road during their service life. This means the avoidance of damage to pavement, which disrupts the nearby business and traffic and occupies the nearby public spaces. The structural reliability and service reliability of UUTs against natural disasters also ensure better living conditions for the victims and prevent many secondary disasters. The environmental improvements provided by UUTs include the removal of visual intrusion (e.g., overhead cables) and construction pollution (e.g., dust and noise).

Since it is an intrinsic feature of social costs/benefits that the causes and consequences are always multiple and entangled, a principle is followed to avoid overlaps among the counted values, which is to focus on the savings of real resources or services (e.g., land, water and time) and ensure exclusivity among them. For example, although natural disasters can also lead to the leakage of directly buried pipelines, the avoided wastage of resources such as water is not counted in the benefit of UUT enhancing urban resistance against natural disasters as having been counted in the benefit of reducing the wastage of resources. A more detailed explanation of the calculation of each benefit category is given in the following sections. After considering the annual growth rate and social discount rate, the final values of all benefits can be united and aggregated in monetary terms. The common base assumption for market price-based approaches makes these values comparable and additive, so further analysis can be made subsequently.

It is worth noting that the benefit of avoiding dust, noise and visual pollution is related largely to personal preference and can hardly be represented with a well-matched market price [49]. However, this is the main environmental benefit of UUTs and should be included. Therefore, CVM has to be adopted to provide a valuation for this benefit. To avoid possible double-counting, this benefit is recommended to be counted but excluded from the total external value of UUTs. Additionally, some important long-term external benefits of UUTs are not included in the benefit factor system because they are not common among UUT projects or require data that are hard to obtain:

1. Reducing water and soil pollution. The leakage of directly buried sewer pipes can pollute the surrounding soil and water, and pollution in the water supply may cause poisoning accidents. Thus, this benefit can be calculated by the expenditures on pollution treatment and medical treatment. However, a gravity sewer pipe is not always integrated into UUTs;
2. Reducing the traffic accident rate. There are many traffic accidents associated with construction sites on the road. Therefore, by avoiding repeated excavation of the road, the implementation of UUTs can reduce the traffic accident rate to a certain degree. However, it is usually not clear what percentage of those construction-associated traffic accidents can be attributed to the construction of directly buried pipelines. The same is true for many other benefits; for example, the reduced risk for some chronic diseases that can be induced by construction pollution.

For specific cases, the benefits above should be counted if conditions allow.

3.2. Evaluation of External Benefits of UUTs

3.2.1. Conserving Urban Land and Underground Space

By housing aerial cables underground and integrating utility pipelines together, the application of UUTs can save space both aboveground and underground. Accordingly, the benefit of conserving urban land and underground space B_1 can be calculated using the following equation:

$$B_1 = P_s A_{s1} + \alpha P_s A_{s2} \quad (1)$$

where P_s is the benchmark land price (yuan/m²), A_{s1} is the area of space saved aboveground (m²), A_{s2} is the area of space saved underground (m²) and α is the correction factor of discounting price of underground space use right, which varies with the function or depth of underground spaces.

The same set of utilities requires a great deal more space in the case of directly buried pipelines, due to the limitation of the minimum net spacing between pipelines. This limitation differs among countries, and is related to parameters such as the diameter of the pipeline. The common situation in China is taken as an example here. The minimum horizontal net spacing between pipelines and between pipelines and buildings are shown in Table 2 [50]. Assume that a UUT replaces a parallel set of all six types of directly buried utility pipelines. In general, the cross-sectional area of the UUT is about 20 m², while that of the latter is $5.0 \times (5.0 + 1.5 + 0.5 + 2.0 + 1.0 + 2.0) = 60 \text{ m}^2$ according to Table 2 (supposing the sum of outer diameters of utilities is 5 meters). That is, approximately two-thirds of the space occupied by a set of directly buried pipelines can be saved. This clearly shows the extent to which UUTs make efficient use of underground space, and that this type of external benefit is nonnegligible.

Table 2. Standard for the minimum horizontal net spacing between pipelines and between pipelines and buildings (m).

	Buildings and Structures	Water Supply	Drainage	Electricity	Telecoms	Heating	Gas
Buildings and structures	—	3.0	2.5	0.6	1.5	3.0	13.5
Water supply	3.0	—	1.5	0.5	1.0	1.5	1.5
Drainage	2.5	1.5	—	0.5	1.0	1.5	2.0
Electricity	0.6	0.5	0.5	—	2.0	2.0	1.5
Telecoms	1.5	1.0	1.0	2.0	—	1.0	1.5
Heating	3.0	1.5	1.5	2.0	1.0	—	2.0
Gas	13.5	1.5	2.0	1.5	1.5	2.0	—

Notes: Only the values of pipelines with the highest standard are included in the table to provide a simple demonstration. Data source: Code for Urban Engineering Pipelines Comprehensive Planning (GB50289-2016) [50].

With the rapid development of UUS, most countries around the world have proposed regulations or policy documents regarding the price of underground space use rights. A proportion of the benchmark land price aboveground is mostly used to assign prices to underground space. For example, Table 3 shows the correction factors for the benchmark land price of underground space in Beijing. For countries or cities without such a document, it is recommended to use correction factors from places with a similar utilization pattern of UUS. Previous studies have also provided thorough evaluations of UUS, including its external benefits, which can be adopted to reveal the potential value of UUS in place of a conservative benchmark land price and correction factors [30,31,51–53].

Table 3. Correction factors of benchmark land price of underground space ^a.

Underground Space Functions	Applicable Benchmark Land Price	Correction Factors		
		For Land Grades 1–2	For Land Grades 3–7	For Land Grades 8–12
Commerce ^b	Price of commercial land	0.80	0.70	0.60
Office	Price of office land	0.30	0.25	0.20
Warehouse	Price of corresponding aboveground land of its main use	0.30	0.25	0.20
Garage	Price of corresponding aboveground land of its main use	0.25	0.20	0.15

Notes: ^a Benchmark land prices of urban land are classified into 12 grades according to the natural and economic attribution of the land, and different correction factors are assigned to corresponding underground spaces based on the aboveground land grade. ^b For underground space with a commercial use, correction factors vary among different floors. Since UUTs are mainly constructed in shallow underground space, only the factors of B1 are presented. Data source: Prescribed by the People's Government of Beijing Municipality, www.beijing.gov.cn.

3.2.2. Reducing the Wastage of Resources

Leakage problems of pipelines over their service life usually cause great loss to properties and lives (as calculated in Section 3.2.7), including resource wastage, casualty accidents and after-effects such as environmental pollution and sinkholes [54,55]. According to the statistics from a World Bank study, the total cost of non-revenue water (NRW) worldwide is about \$141 billion per year, and a third of this is incurred by developing countries, with an estimated 45 million cubic meters of water lost daily through water distribution system leakage [56]. Similarly, a total of 7808.73 million cubic meters of water and 3381.76 million cubic meters of natural gas were lost in China in 2016, mainly owing to pipeline leakage [57]. Most of those leakages were caused by excavation or other outside force damage, corrosion and material or equipment failure, as suggested by the investigations of government departments and organizations such as the Pipeline and Hazardous Materials Safety Administration of the U.S. (PHMSA), European Gas Pipeline Incident Data Group (EGIG) and United Kingdom Onshore Pipeline Operators Association (UKOPA). Under these circumstances, it is difficult for authorities to persuade people to save resources, which further worsens the resource condition [58].

By means of UUTs, the situation can be greatly improved. The convenient condition for a maintenance and strengthened monitoring system can first drastically reduce the occurrence of situations such as outside force damages and then control the volume of leakage to a minimum by initiating emergency measures at once.

Thus, to reflect this advantage of UUTs, the benefit of avoiding the wastage of resources is computed as follows:

$$B_2 = \sum_n \sum_{t=1}^y P_{wn} \cdot (1 + a_{2wn})^t (1 + r)^{-t} \quad (2)$$

where P_{wn} is the value difference between leaked resource category n of a directly buried pipeline and of a UUT per year (yuan/year) and a_{2wn} , r and y refer to the annual growth rate in terms of P_{wn} , the social discount rate and overall calculation period (measured in years), respectively, to take the time value of money into account, and this discount will be included in most of the benefit valuations below with only a change to a_{2wn} , which will not be explained repeatedly.

Normally, P_{wn} can be calculated as the product of the difference in the amount of pipeline leakage between a directly buried pipeline and UUT per length per year, the total length of the UUT project and the corresponding average fee. Due to the international concern regarding resource wastage, relatively complete statistical records of pipeline leakage can be easily obtained. If the leakage volume classified by the variety of uses of water or gas is available, then a weighted average fee can be applied; if not, it is also valid to make do with an approximate mean value.

3.2.3. Avoiding Disruption to Local Business

According to several studies, local business sales decrease due to the influence of repeated excavation and reinstatement procedures of directly buried pipelines [17,21,24,59,60]. Although the business sales lost by one shop onsite may be gained by another within the same municipality, the stability of the economic environment is impaired and net social loss has resulted. Inconvenience has also been caused to regular customers of the affected businesses. The maintenance and renovation of UUT pipelines can be carried out inside the tunnel, avoiding occupying roads and sidewalks with construction sites and consequently blocking access to local businesses. Moreover, the air and noise pollution caused by aboveground construction, which makes stores less appealing and results in turnover drops, can also be circumvented in the UUT setting. To reflect this advantage of UUTs, the

benefit of avoiding disruption to local businesses is calculated using the claimed income loss of onsite business as follows:

$$B_3 = \sum_{t=1}^y P_b \cdot D \cdot (1 + a_3)^t \cdot (1 + r)^{-t} \quad (3)$$

where P_b is the daily business loss in the area of the pipeline affected by E&R if directly buried pipelines were built rather than a UUT (yuan/day), D is the number of pipeline E&R days which can be eliminated by adopting a UUT per year (days/year) and should be the product of the average E&R frequency of a directly buried pipeline per length per year, the total length of the UUT project and the number of pipelines that are to be integrated into the UUT, a_3 is the annual growth rate in terms of P_b .

For projects in built-up areas, information about the affected local businesses is basically confirmed. Thus, P_b can be estimated according to surveys of affected businesses [16,59,61]. Generally, businesses are impacted to different extents in terms of their types and locations, and so are their percentages of turnover loss. The survey method, although it requires more effort, is therefore able to perform the evaluation more precisely. Nevertheless, when difficulty in performing surveys is faced—for example, for UUT projects planned in new urban areas—it is optional to use the benefit transfer method and adapt the average daily loss of businesses affected by pipeline E&R from existing research or statistics in other cities or areas, with a correction factor considering economic development, prices of commodities and other condition differences.

3.2.4. Avoiding Traffic Delays

By keeping maintenance and renovation work underground, UUTs are also free from disrupting traffic, which can result in extended travel time, more vehicle wear and tear and increased petrol consumption [21,26,59,61]. Since directly buried utility pipelines that can be integrated into UUTs are arranged underneath sidewalks or roadways, or both, varying from city to city and case to case, extended travel time can be incurred for either vehicle passengers or pedestrians, or both. Therefore, the benefit of UUTs in terms of avoiding traffic delays is expressed in three kinds of combination of two broad categories: B_{4p} for avoiding pedestrian delays and B_{4v} for avoiding vehicle delays.

$$B_4 = \begin{cases} B_{4v} \\ B_{4p} \\ B_{4v} + B_{4p} \end{cases} \quad (4)$$

B_{4v} mainly consists of two parts: (1) the value of travel time savings (VTTS) for in-vehicle travelers, and (2) values derived from vehicle operation, such as the reduction in vehicle wear and petrol consumption. This can be expressed as in the equation below [21,25,26]:

$$B_{4v} = \sum_{t=1}^y \left[t_v \cdot Q \cdot T \cdot D \cdot N_{pv} \cdot P_v \cdot (1 + a_{4v})^t \cdot (1 + r)^{-t} + P_{vo} \cdot (1 + a_{4vo})^t \cdot (1 + r)^{-t} \right] \quad (5)$$

where t_v is the extra travel time needed for each vehicle to pass through the affected zone compared with the passing time before construction (often at the minute level and therefore needs to be translated into hours/vehicle), Q is the average hourly traffic (vehicles/hour), T is the number of hours per day that traffic is disrupted due to E&R (hours/day), D is the same as mentioned in Section 3.2.3, N_{pv} is the average number of passengers in the vehicle (persons/vehicle), P_v is the local VTTS for in-vehicle travelers (yuan/hour), P_{vo} refers to the possibly saved values associated with vehicle operation (yuan/year), and a_{4v} and a_{4vo} are the annual growth rates in terms of P_v and P_{vo} , respectively.

Research works in the field of transportation have developed many effective but complicated traffic models that can be used to calculate delay time, some of which have

already been adopted in the calculation of the social benefits of utility projects [13,26]. However, those models are mostly complicated and require detailed classification and data, which is laborious and difficult for many UUT projects that are planned in new urban districts. For example, there are at least three different kinds of vehicle delay (speed delay, queue delay and detour delay) calling for different equations and numerous parameters, respectively, meaning that t_v can have at least three different values. To cope with this situation, a generalized method is recommended here. Supposing a road section of 400–500 m is adversely affected by an E&R, the difference between the travel time through this section on foot (5 km/h) and by vehicle (50 km/h) is about 4–5 min, which can be used for the estimation of t_v . Then, to avoid possible overestimation and to simplify the calculation, a conservative assumption that extra passing time is needed only in rush hours is made, enabling T to be estimated as 4 h per day (two for the morning and two for the evening) and Q to be simply the rush-hour volume of traffic.

According to previous research works, VTTS varies widely in different regions with different valuation methods [62,63]. In most cases, a complex stated preference method with a high level of expert knowledge and effort is employed, while uncertainty remains in the fundamental assumptions of the survey and the answers of respondents [64]. Some countries, such as the UK, the US and the EU countries, initiate official research to assign VTTS every several years [63,65–67]. It is reliable and convenient for local projects to follow the official instructions and use the official VTTS in evaluation. For projects in developing countries with an absence of official VTTS and insufficient statistics, the methods (shown in Table 4) provided by the World Bank are acceptable [68].

Table 4. Methods for valuing in-vehicle-time (IVT) savings recommended by the World Bank.

Approach to be Adopted	For Work Time	For Non-Work Time
Base approach	Option 1: national average wage rate adjusted by observed adjustment factors Option 2: $1.33 \times$ wage rate (adjusted by shadow wage rate)	Adults: $0.3 \times$ household income (per head) Children: $0.15 \times$ household income
Ideal approach	Adjusted from observed wage rate using observed adjustment factors such as overheads and shadow wage rate	Revealed and Stated Preference methods for VTTS and modifiers with results adjusted to price base

Notes: The value of travel time savings (VTTS) of walking during work time is the same as that of IVT, and the VTTS of walking during non-work time is modified as $1.5 \times$ the corresponding value for IVT. Data source: Mackie, P., Nellthorp, J., & Laird, J. (2005). Valuation of time savings (Report). No 33936, the World Bank, Washington, D.C., <http://documents1.worldbank.org/curated/en/424721468176986221/pdf/339360rev0trn0150EENote2pdf.pdf>.

Except for vehicle types and ages, pavement roughness levels, local oil prices and vehicle maintenance costs [69], P_{v0} is also related to local driving habits such as stop-and-go cycles and vehicle speed changes [25], which vary between cases and rely on investigation and study conducted in the locality. For example, a study report by Beijing Jiaotong University suggested that all private cars together suffered a congestion mileage of about 33.45 billion kilometers, with an extra energy consumption of 2.6 L of petrol per hundred kilometers, resulting in an energy cost of nearly 5 billion CNY in total in Beijing in 2008 [70]. For cities or regions without relevant data or research, P_{v0} can be adapted from cases under similar conditions, with adjustments simply made for oil prices and maintenance costs as an approximation.

B_{4p} represents the VTTS for pedestrians [26]:

$$B_{4p} = \sum_{t=1}^y t_p \cdot N_{pd} \cdot P_{pd} \cdot D \cdot (1 + a_{4p})^t \cdot (1 + r)^{-t} \quad (6)$$

where t_p is the extra time added for a pedestrian to pass through the area (often at the minute level and therefore needs to be translated into hours/person), N_{pd} is the average

number of pedestrians affected per day (persons/day), P_{pd} is the local VTTS for walking (yuan/hour), D is the same as above and a_{4p} is the annual growth rate of P_{pd} .

A generalized method for estimating t_p is also recommended for calculating B_{4p} . Supposing a street section of 500 m is adversely affected by an E&R construction, with a site 50 m long and leaving an area of one meter wide for pedestrians to pass through. The prolonged passing time through a street section such as this is usually between 10 and 12 min, while normally it only takes people 5 to 7 min, so t_p can be estimated at 5 min per person. In addition, it is usually more difficult to gather traffic data for pedestrians than vehicles, so the aforementioned conservative assumption is still recommended, assuming N_{pd} to be approximately the number of pedestrians in the 4 h of maximum traffic. The method for obtaining P_{pd} is the same as suggested above, as most of the official instructions have defined VTTS for walking as well, and the rest without official instructions can refer to the study of the World Bank in 2005 [68].

3.2.5. Conserving the Service Life of Pavement

Except for onsite business loss and traffic delays, repeated E&R procedures for directly buried pipelines can also do irreversible damage to the pavement, leading to replacement expenditure and premature deterioration. This can also be avoided by using UUTs. While the pavement replacement expenditure, which, as part of the maintenance construction cost, is usually included in the internal direct cost of directly buried pipelines and excluded in that of UUTs, is not under consideration here, the value of pavement service life reduction that is avoided is used to represent the UUT benefit of conserving the pavement service life B_5 .

The study of Tighe et al. [13] stated that a new road in Ontario subjected to an open excavation can suffer an approximately 30% reduction in its service life. This conclusion was then used widely to evaluate pavement service life loss by the life cycle costing method and the replacement cost method, which take the original construction cost of the pavement as a substitute of the value of pavement's designed service life [17,26]. It was also suggested by Tighe et al. that an older road suffers less than a new road because of the existing distresses in the structure due to ageing. However, the quantitative relationship between road ages and the percentage of pavement life loss has not been made clear; neither has the effect of a second or third E&R on the same spot on the pavement. It can only be speculated that repeated E&R on the same spot of the pavement will cause an increasingly small reduction of the pavement's service life. Consequently, for a simple and rapid estimation of B_5 , it is first calculated with the assumption that each E&R occurs on a different spot on the pavement of a new road, and is then discounted by a correction factor, as shown in the following equation [17]:

$$B_5 = \sum_{t=1}^y \beta \cdot P_{pm} \cdot A_{E\&R} \cdot \left[-\frac{1}{L_{pm}} + \frac{1}{1+(1-k) \cdot (L_{pm}-1)} \right] \cdot F \cdot (1+a_5)^t \cdot (1+r)^{-t} \quad (7)$$

where P_{pm} is the original construction cost of pavement per square meter, which is used as a proxy for the value of pavement service life (yuan/m²), $A_{E\&R}$ is the average area of construction site for a pipeline E&R procedure (m²/time), L_{pm} is the designed service life of the pavement (years), k is the percentage of pavement service life loss when the pavement of a new road experiences E&R for the first time, F is the frequency of pipeline E&R, which can be eliminated by adopting a UUT(times/year)—it should be noticed that this is different from D , β is the correction factor considering that not all roads are newly built and not all E&R procedures happen on different spots, which should be decided in terms of local situation and a_5 is the annual growth rate of P_{pm} .

It is worth noting that the value of k is not perpetually equal to 0.3, since Tighe et al. base their study entirely on the foundation of situation in Ontario, with pavement performance depicted based on the relevant manual of the Ministry of Transportation of Ontario and other relevant research works conducted locally. Therefore, for projects in

cities in which the weather and soil conditions are similar to that in Ontario, a value of 0.3 can be simply adopted as the value of k , while for others, k should be decided based on local research or at least a qualitative comparison between local conditions and Ontario.

3.2.6. Conserving Aboveground Public Space

Aboveground E&R procedures in the road can also take up public spaces (e.g., parks, squares and parking spaces) at the roadside. The corresponding public services provided by the municipality are therefore lost, while the land, construction, etc., for providing them have already been used. The implementation of UUTs can avoid this wastage. The benefit is recommended to be counted as the avoided loss of roadside parking revenue, as shown in Equation (8) [25,26], because roadside parking is one of the few public services that have a defined price.

$$B_6 = \sum_{t=1}^y P_{rp} \cdot N_{rp} \cdot D \cdot (1 + a_6)^t \cdot (1 + r)^{-t} \quad (8)$$

where P_{rp} is the local average parking fee for a roadside parking space (yuan/parking space), N_{rp} is the average number of roadside parking spaces occupied by an E&R procedure of directly buried pipes (parking spaces), D is the same as above and a_6 is the annual growth rate of P_{rp} .

Parking spaces at the roadside usually charge differently at different times of a day and for different amounts of time, and sometimes they are empty. Therefore, P_{rp} should be estimated on the basis of local statistics of parking, or taken as half of the full daily charge of a parking space. For cities or areas in which vehicles do not pay for parking at the roadside, the local fee for parking at open parking lots can be taken as a proxy. N_{rp} can be calculated based on the length of the construction site and of a parking space.

3.2.7. Reducing Serious Accidents of Urban Pipelines

By avoiding careless nearby excavation damage and providing instant emergency measures with close monitoring, UUTs can greatly reduce the occurrence of serious pipeline accidents, which may involve fires or explosions and cause human injury and death. Huge economic loss can therefore be prevented, apart from those non-accidental external costs brought by routine maintenance, as counted in the previous sections. This benefit of reducing serious accidents is expressed with the equation below:

$$B_7 = \sum_{t=1}^y \left[P_{pp} \cdot (1 + a_{7p})^t \cdot (1 + r)^{-t} + P_{hc} \cdot (1 + a_{7c})^t \cdot (1 + r)^{-t} \right] \quad (9)$$

where P_{pp} is the value of annual public property loss due to pipeline accidents in the project service area if directly buried pipelines were built rather than UUTs (yuan/year), P_{hc} is the cost of human casualties incurred by pipeline accidents in the project service area (yuan/year) and a_{7p} and a_{7c} refer to annual growth rates of P_{pp} and P_{hc} , respectively.

A large proportion of those accidents are gas pipeline accidents, arousing great concern and consequently leading to more detailed records. Statistics provided by the Underground Pipeline Committee of China Association of City Planning indicate that, from 2009 to 2013, gas pipeline accidents accounted for 54.6% of all massive pipeline accidents in China. Therefore, this benefit can also be estimated based on the data of gas pipeline accidents multiplied by a scale factor, if there is trouble obtaining data for all types of pipeline accidents.

In the field of pipeline risk assessment, the quantitative risk assessment of pipelines is usually based on the failure probability of different causes, which is decided by the fuzzy fault tree method in cases with insufficient accident data, and the cost of corresponding consequences [71]. To simplify the calculation, it is recommended to omit the process of classifying accidents by detailed causes. Subsequently, P_{pp} and P_{hc} only need to be valued based on statistics of local pipeline accidents as a whole. The former can be simply calculated using market prices or obtained through statistics provided by governments,

while the latter, which do not include goods and have no market price to refer to directly, should be calculated in monetary terms with the help of human capital methods. The modified human capital method evaluates premature death as a loss of contribution to society for a certain period of time, using the product of local GDP per head and the years of life lost, and the human capital method can be used to evaluate the loss of labor due to human injury by multiplying the local average wage rate by the duration of convalescence. For new urban areas, it is better to adapt statistics from places with a similar level of urban management as well as living habits and make adjustments by a scale factor in the total length of pipelines.

3.2.8. Enhancing Urban Resistance against Natural Disasters

By accommodating buried pipelines and aerial cables into utility tunnels, UUTs shelter most of the utility pipelines from destructive natural disasters such as earthquakes and wind storms, and prevent a large number of secondary disasters from occurring. It has been indicated in previous research works that the seismic response of pipelines gathered in UUTs is greatly reduced compared with that of traditional buried pipelines, with an almost unnoticeable increase in the additional dynamic stress when the peak ground acceleration (PGA) rises from 0.5 g to 3.0 g [72,73]. Information regarding disasters in the past also suggests that UUTs have a stronger resistance against disastrous events. For example, in the 1995 Hanshin-Awaji Japan earthquake, a large number of infrastructures were devastated, while the utility tunnels were reported to have suffered no overt destruction, and even the ground surface immediately above the UUTs remained in a rather good condition due to the reinforcement measures around UUTs. On the other hand, the failure of buried water pipes during the Hanshin-Awaji earthquake not only resulted in countless fires that were unable to be put out in a timely manner but also led to the temporary closure of many local businesses and industries that survived, causing a large degree of economic loss. As they are structurally reliable, UUTs can provide emergency response and support services continuously for areas with potential vulnerability [48] and consequently enhance urban resistance against natural disasters. Therefore, the corresponding benefit B_8 can be calculated as the sum of two parts: (1) the avoided rehabilitation expenditure of the buried pipes that are damaged during disasters, which can be estimated by the construction cost of equivalent pipes, and (2) the value of municipal services that UUTs can conserve while directly buried pipelines may fail during disasters.

$$B_8 = \sum_i \sum_n \gamma_i \cdot [P_{cn} \cdot l_{in} + (P_{nL} \cdot N_{pi} \cdot D_{in} + P_{IBi} \cdot D_{IBi})] \quad (10)$$

where i stands for different types of disasters in the locality, n stands for different types of damaged buried pipes that can be integrated into UUTs, as well as the corresponding interrupted municipal services, P_{cn} is the construction cost of an equivalent buried pipe n per unit length (yuan/kilometer), l_{in} is the average of the total damaged length of buried pipe n once disaster i has occurred (kilometer), P_{nL} is the value of municipal service n for daily life (yuan/person·day), N_{pi} is the average population in the affected area of disaster i (persons), D_{in} is the duration of the interruption of service n once disaster i has occurred (days), P_{IBi} is the daily value of municipal services for industrial production and business activities that are affected by disaster i (yuan/day), D_{IBi} is the average duration of closure of affected industries and businesses during disaster i (days) and γ_i is a factor associated with the probability and frequency of disaster i occurring in the locality during the service life of UUTs.

P_{nL} can be estimated by the expenditure of bottled water, heating energy, illumination energy, etc., using the substitute cost method [17]. In terms of telecommunication pipelines, it is difficult to find a substitute, and so public WTP for avoiding losing access to telecommunication can be adopted. P_{IBi} can be estimated based on local industrial and business output over the years, with the average percentage of industry and businesses that are temporarily closed in the locality during disaster i . For cities or areas without those

statistics, the benefits transfer method is required again, and under this condition, there is no need to adapt all types of the data stated above. A general estimation based on the ratio of the direct economic loss to indirect economic loss of disasters is recommended for the reason that most of the indirect losses that occur in natural disasters are initiated by the failures of lifeline projects, as revealed by previous major disasters.

3.2.9. Avoiding Dust, Noise and Visual Pollution

In addition to the aforementioned negative results, the aboveground E&R procedures of directly buried pipelines also generate a great deal of dust and noise in the vicinity, which is not only polluting and irritating but can also cause diseases to human skin and the respiratory tract. Together with the visual intrusion imposed by aerial cables and E&R construction sites, these drawbacks are too subjective to be evaluated based on real market prices. Consequently, the stated preference method is usually required to evaluate this kind of external benefit, as shown in Equation (11) [30,49].

$$B_9 = \sum_{t=1}^y P_{WTP} \cdot N \cdot (1 + a_9)^t \cdot (1 + r)^{-t} \quad (11)$$

where P_{WTP} is the average amount of money each respondent is willing to pay annually to get rid of the dust, noise and visual pollution caused by buried pipe E&R procedures and aerial cables by adopting a UUT (yuan/person·year), N is the number of people living or working in the service area of the UUT project (persons) and a_9 is the annual growth rate in terms of P_{WTP} .

In the questionnaire used to obtain P_{WTP} , the description of the scenario was required to be understandable and sufficiently detailed to convince respondents that the UUT project was real and possible to construct. On the other hand, the description was also required to be carefully limited to dust, noise and visual pollution without the implementation of UUTs to try to minimize double counting. Open-ended questions or dichotomous choice questions could be used to determine how much each respondent was willing to pay to be rid of those sources of pollution by adopting another type of infrastructure. Since respondents tend to behave strategically when surveyed on their WTP for public goods, the payment mechanism and other details was also required to be provided clearly to convince respondents that the price they suggest could actually be charged. Additionally, the sample size needed to meet the requirement of the acceptable sampling error. After analyzing the returned questionnaires regarding the characteristics of respondents and on proposed payments, outliers needed to be identified and removed before calculating the final value of P_{WTP} , and the choice among means, medians and trimmed means needed to be made deliberately [74]. A retest with the same survey after a reasonable time gap with the same group of respondents or a different group in the same population could be carried out to justify the reliability of the surveys [75].

4. Case Study

Xiong'an New Area, established in 2017, is located at the center of the triangular area formed by Beijing, Tianjin and Baoding, as shown in Figure 3. It is a new area of national significance which aims to relieve Beijing of non-essential functions in its role as China's capital, and many of the construction standards for Xiong'an are the same as those for Beijing. It covers an area of approximately 2000 km², of which 198 km² is planned as the starting area and is now under construction. The central downtown of the starting area is estimated to be completed around 2035 with advanced urban infrastructure, including a large UUT network.

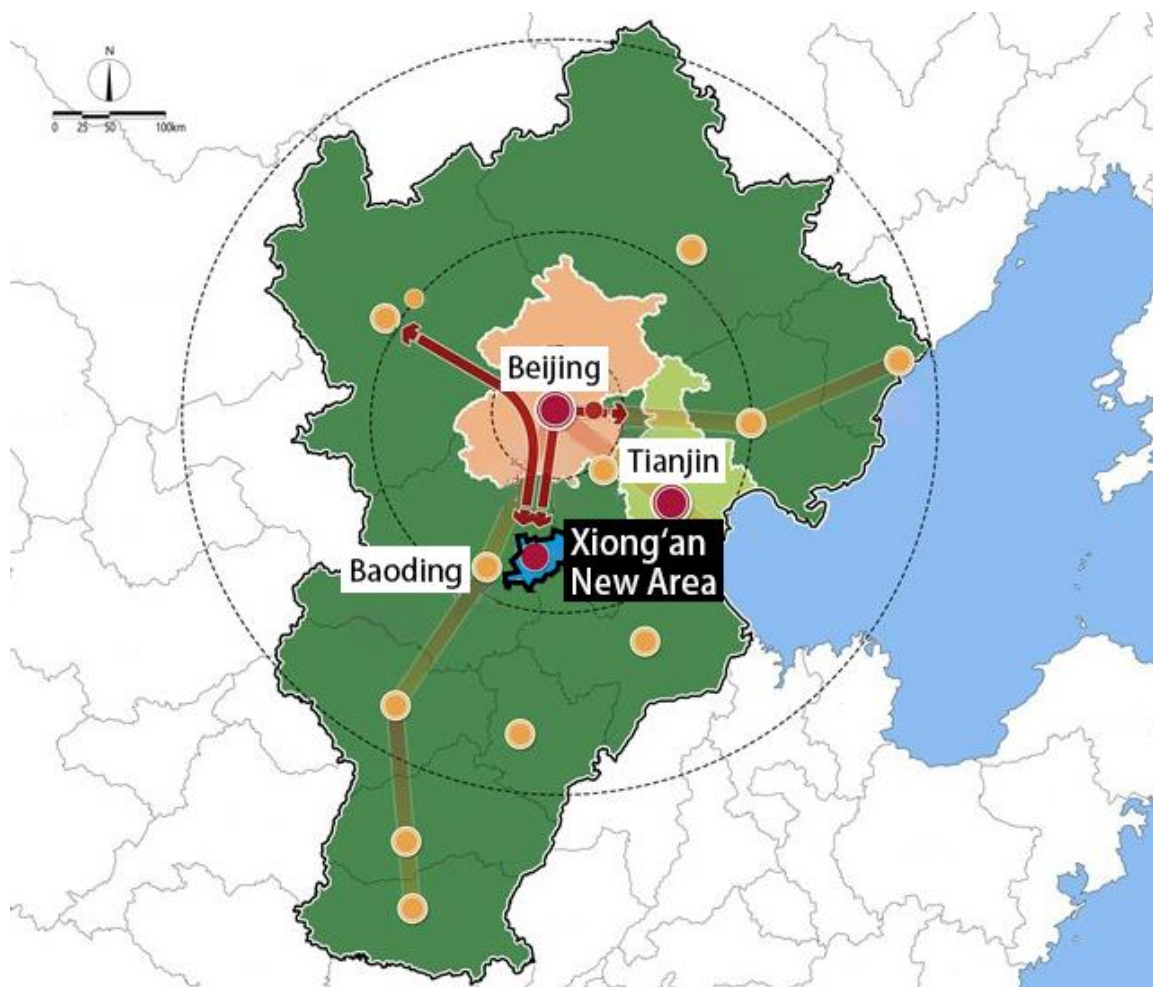


Figure 3. Location of Xiong'an New Area (adapted from the Regulatory Detailed Plan for the Starting Area of Xiong'an New Area, www.xiongan.gov.cn).

According to the Regulatory Detailed Plan for the Starting Area of Xiong'an New Area (2020–2035), an eco-friendly and livable urban area is going to be built that will accommodate a population density of 10,000 inhabitants per square kilometer of construction land. Urban infrastructure, such as UUTs of a high quality, is planned to lay a solid foundation to promote green and low-carbon lifestyles and modes of production. For urban safety reasons, the layout of UUTs in Xiong'an and the layout of pipelines in the UUTs are withheld; however, the road network planned in Xiong'an, shown in Figure 4, can provide an approximate description. According to the special planning for urban utility tunnels of Xiong'an New Area, as of 2035, there will be 90 km of UUT mainlines and 100 km of branches lying beneath sidewalks and greenbelts of arterial and secondary trunk roads all over the city, with a service life of 100 years. Municipal pipelines, including water distribution pipes, gas supply pipes, electricity transmission lines, telecoms lines and heating pipes, are going to be accommodated into UUTs, except for the storm water sewer due to its excessive cross-sectional area.

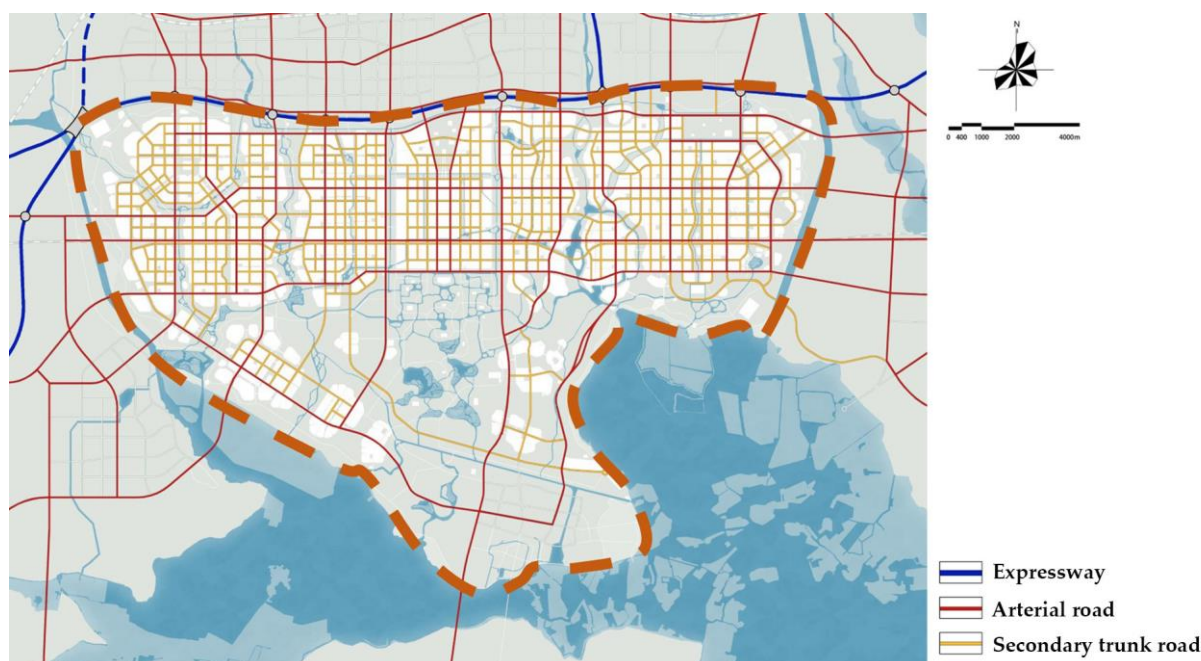


Figure 4. Layout of road network in the starting area of Xiong'an New Area (adapted from the Regulatory Detailed Plan for the Starting Area of Xiong'an New Area, www.xiongan.gov.cn).

Based on the planning documents, the external benefits of the UUT throughout its service life (100 years) in Xiong'an New Area are calculated using the methods proposed above. Detailed data and corresponding notes can be found in the Supplementary Materials. Since Xiong'an New Area is newly established, with almost none of the required statistics, parameters that are not predicted by the planning documents of Xiong'an New Area are adapted from elsewhere (mainly Beijing). The construction of UUTs is completed successively, so it is supposed for the ease of calculation that the project will be finished in 2020, along with the beginning of the benefits. Therefore, all of the following monetary values are converted to the prices in 2020. Additionally, as it is difficult to make a proper prediction of different kinds of annual growth rates, especially in an unbuilt area, all the annual growth rates are set at 8% for simplification, which is the same as the social discount rate suggested by the National Development and Reform Commission (NDRC) and Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD) [76]. The valuation results are listed in Table 5.

Table 5. Valuation results of the case study of Xiong'an New Area (100 years).

External Benefit Category	Description	Value (CNY mn.) (Price in 2020)	Proportion
B ₁	Conserving urban land and underground space	14,615.39	31.77%
B ₂	Reducing the wastage of resources	3543.39	7.70%
B ₃	Avoiding disruption to local business	12,146.12	26.40%
B ₄	Avoiding traffic delays	14,228.83	30.93%
B ₅	Conserving the service life of pavement	35.47	0.08%
B ₆	Conserving aboveground public space	—	—
B ₇	Reducing serious accidents of urban pipelines	584.38	1.27%
B ₈	Enhancing urban resistance against natural disasters	848.05	1.84%
	Total	46,001.63	100%
B ₉	Avoiding dust, noise and visual pollution	14,235.00	—

The total external benefit of UUT in Xiong'an New Area reaches 46 billion yuan (price in 2020). According to the project budget estimates in the planning documents, the total investment of the project will be around 22.8 billion yuan (price in 2020), and the monetary value of external benefits is more than twice of that, which again demonstrates the huge contribution of UUT projects to people's livelihood. Most of the UUT projects in China are invested in by the public sector for the general welfare of better municipal services, and the problem of the huge cash flow for the public sector can sometimes hinder the implementation of UUTs.

However, the top four benefits (B_1 , B_3 , B_4 and B_9) shown in Table 5 point towards a tendency and corollary of cooperation with a better equilibrium among diversified subjects; i.e., the government, the general public and the retailers along the street. The benefit of conserving urban land and underground space (14.6 CNY bn) is most directly linked to government finance; the benefit of avoiding traffic delays (14.2 CNY bn) and the benefit of avoiding dust, noise and visual pollution (14.2 CNY bn, although not comparable with other market price-generated values, still indicates a huge benefit) embody public wishes for upgrades to infrastructure and improvements to quality of life; and the benefit of avoiding disruption to local business (12.1 CNY bn) indicates the degree to which business can benefit from UUTs projects. Furthermore, any one of B_1 , B_3 and B_4 covers more than half of the project budget. Theoretically, pipeline companies and energy companies, which are state-owned in China, should have been the fourth subject in the cooperation of UUTs. Nevertheless, the benefits directly received by them have a relatively small monetary value, which are B_2 , B_5 and B_7 (accounting for about 4.2 CNY bn or 9.05% in total). This may be part of the reason why pipeline companies usually have a lower motivation for utilizing UUTs. However, it is noteworthy that the benefit of reducing serious accidents of urban pipelines (B_7) (0.58 CNY bn) is mainly associated with the value of time or human capital and is therefore inevitably underestimated. Specifically, a rather low accident rate is adapted from the data of Beijing and used in the calculation here, and part of the credit should be given to the government for its high level of management. In conclusion, it is not that pipeline companies benefit less from UUTs, but that other social subjects have always borne a large part of the costs for them in the context of directly buried pipelines, and some of these costs have not been made clear or added to the total cost assessment in existing research. Additionally, it is indicated that the present charges for the external costs of pipeline companies may have not reached an ideal internalization. Therefore, further study is required to be conducted on the external cost–benefit assessment of UUTs based on the classification of social subjects. Traditionally, the externalities of UUTs are classified into two categories, which are the social benefits/costs and the environmental benefits/costs. Sustainability is taken as a means rather than an end in this situation. By positioning the economic aspect of UUTs in opposition to the environmental and the social aspects, a more winding road may have been chosen to pursue sustainability. On the other hand, the allocation of social resources is profoundly influenced and motivated by relationships between different social subjects, which is widely acknowledged. From this aspect, the classification by social subjects works deliberately to recognize the different roles each social subject plays in the utilization of UUTs and mitigates the opposition during the evaluation process. In this way, better sustainable development may be obtained, and broader public participation may be promoted.

It is unsustainable for governments to invest in UUT projects alone due to the enormous financial burden placed by the high construction cost. To improve the efficiency of urban construction and the allocation of social resources, it is of great significance to apply varied financing modes and attract diversified investors. Among the four subjects mentioned above, pipeline companies are the most direct beneficiaries of UUT projects and also the primary partners. However, as the traditional cost-sharing system (such as the spatial proportional method and the directly buried cost method) mainly emphasizes the sharing of the construction and operation costs of UUTs and fails to consider the distinguishing features of operation of different pipes, the benefits of UUT projects

are not made clear for the pipeline companies, making it seemingly compulsory and of a low yield for them to participate in the projects. Pipeline companies are consequently reluctant to support the utilization of UUTs. To cope with this situation, a large number of research works have been undertaken to improve the fairness and satisfaction in cost-sharing among pipeline companies, mainly by combining different allocation methods and decision theories [77–80], in which the benefit-based proportion is also put to use, although greatly simplified. Nevertheless, the complaints of unfairness are principally generated from the fact that pipeline companies recognize themselves as passive undertakers. To make a fundamental improvement, the benefits of UUTs need to be stressed not only in terms of their values but also for their beneficiaries. The calculation of each external benefits proposed in this paper can be carried out separately on each type of pipeline if the data required have been collected beforehand and then be used to incentivize pipeline companies more practically.

Another factor to note is that the benefit of enhancing urban resistance against natural disasters is usually one of the biggest advantages of UUTs, yet it is not significant in this case. This is principally because, compared to other external benefits which are based on events that occur a couple of times each year throughout the service life of UUTs, this benefit is merely derived from a single earthquake over the whole 100 years in this paper, which also means that, once the earthquake occurs, a great amount of benefit will be generated in a short time. Moreover, the value of this benefit seems small, but this is incorrect. An earthquake of magnitude eight, which is predicted to be likely to occur in the Tangshan earthquake region where Xiong'an is located in the next 50 years [81], often causes huge amounts of economic loss, as suggested by history. According to the prediction method adopted in this paper, the total economic loss (including direct loss and indirect loss) of this possible earthquake is estimated to be approximately 1277.74 million CNY, and the loss that could be prevented by the UUT (B_8) (848.05 million CNY) would account for 66.4% of that.

The calculations above are conservative and mainly based on common parameters such as the number of directly buried pipe E&R days or times per year. Therefore, it is reasonable to represent the external benefits of UUTs with the valuation results and make comparisons between different categories.

5. Conclusions

UUTs make significant contributions to urban sustainable development by facilitating the operation, maintenance and renewal of the utility pipelines inside them and bringing huge external benefits. It is not reasonable to hinder the utilization of UUTs merely due to the high initial construction costs. The external benefits of UUTs during their service life need to be quantitatively evaluated and taken into consideration during decision making and resource allocation. This paper proposes the composite market price method to make a scientific and feasible monetary evaluation of the long-term external benefits of UUTs. A benefit factor system of nine external benefit categories of UUTs is also built systematically. The method and the benefit factor system are then applied to the case study of Xiong'an New Area for demonstration and validation. The following conclusions are drawn:

1. The composite market price method was proposed, which evaluates each external benefit of UUTs with the suitable market price-based valuation method and provides comparable and additive values in monetary terms. By aggregating these values, a strictly conservative evaluation with certainty was developed that can win recognition from governors and private sectors.
2. A long-term external benefit factor system of UUTs was built, which was systematically based on the acknowledged advantages of UUTs over directly buried pipelines, avoiding omissions or overlaps as much as possible. Specifically, the factor system includes the benefit of conserving urban land and underground space, reducing the wastage of resources, avoiding disruption to local business, avoiding traffic delays, conserving the service life of pavement, conserving aboveground public space, reduc-

ing serious accidents of urban pipelines, enhancing urban resistance against natural disasters and avoiding dust, noise and visual pollution.

3. Instructions on the adoption of valuation methods, the selection of parameters and reference criteria were provided accordingly, with which the composite market price method can be applied to both old districts and new urban areas, with or without sufficient data.
4. The case study of the UUT projects in Xiong'an New Area showed that, although the composite market price method is intrinsically conservative, the external benefits of UUTs still outweigh the initial construction cost to a great extent. The fact that UUTs possess unexpectedly huge benefits was revealed. The validity and feasibility of the composite market price method in evaluating UUT projects was, therefore, also demonstrated.

The results of the case study also indicated that the valuation can be further improved in two aspects to provide stronger support for the cooperation and sharing of responsibility in utilizing UUTs. One is to classify the external benefit categories of UUTs in terms of the social subjects that are most directly affected, namely the government, the general public, the retailers along the street and pipeline companies. The other is to carry out an externality assessment of UUTs separately on each type of pipeline. For these objectives, further study on the external benefit categories and the assessment method is still needed. The collection of the required data also needs to be taken seriously and performed beforehand.

Supplementary Materials: The following are available online at <https://www.mdpi.com/2071-1050/13/2/900/s1>, Table S1: Data used in the case study of Xiong'an New Area. The construction of UUTs is completed successively, so it is supposed for ease of calculation that the project would be finished in 2020, along with the beginning of the benefits. The time horizon of the benefit evaluation is 100 years from 2020 to 2120, which corresponds to the designed service life of the UUTs. The data and calculations in the table follow the requirements of the calculation methods proposed in Section 3.2., with all unit prices presented according to the monetary value in 2020. E&R: excavation and reinstatement. References [82–85] are cited in the supplementary materials.

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