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Dynamic Transportation Planning and Operations: Concept, Framework and Applications in China

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Abstract

Transportation systems are large, complex and dynamic. Traditional transportation planning methods are based on 4-step travel demand forecast models, which are not good at describing the dynamic characteristics of transportation systems. On the basis of the existing research, this paper presents the concept of Dynamic Transportation Planning and Operations (DTPO), and explains the connotation and application of DTPO in recurrent and non-recurrent scenarios. In addition, a simulation-based DTPO Approach (SDTPOA) is put forward and a DTPO Platform which integrates travel demand model and traffic simulator is designed. The functions of each module in the DTPO Platform are explained in details as well as the operating mechanism of the platform under both recurrent and non-recurrent situations. The DTPO Platform adopts agent-based travel demand model, which can depict the real world better so as to replace the conventional travel demand models. As the key component of the DTPO Platform, Agent-based Modeling (ABM) is analyzed in this paper.

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1. Introduction

China’s economic development has made a remarkable achievement in the past three decades. As a consequence, the national urbanization and motorization continue to improve with a considerable accelerating

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rate, which triggers a fast increase in urban travel demand. For example, the annual average growth rate of vehicle ownership of Beijing is 10.91% from 2000 to 2008, and in July 2012, the vehicle ownership has reached 5.12 million. However, urban transportation infrastructure and traffic management fail to match the rapid growth rate of travel demand, thus sharpening the contradiction between travel demand and supply. The annual average growth rate of the total urban road length is relatively as low as 3.64%. Currently, serious traffic congestion shocks China’s big cities. For example, the average travel speed at peak hours is only approximately 20 km/h in Beijing. In addition, the traffic accident rate also continues growing, and the pollution from automobile emission becomes more and more prominent. These problems caused by the unexpected increase of traffic demand continue to trouble citizens in China, mainly because the transportation system lacks efficient planning and operation strategies. Therefore, scientific and rational transportation planning theory and practice are in more and more urgent need to accurately predict travel demand, optimize resource allocation of transportation systems, and provide citizens with effective guidance to their travel behaviours.

Traditional transportation planning uses the four-step method, i.e. trip generation, trip distribution, modal split and assignment (Sheffi, 1985), for travel demand forecasting. It assumes that travel demand maintains static in the planning period, then estimates annual, seasonal, weekly and daily travel demands based on household travel survey for road network planning in the next few years or decades. However, the field travel demand is time dependent, e.g. each OD pair and link flow vary with time. Traditional static planning methods cannot precisely describe time-dependent travel demand and dynamic traffic flow characteristics, so it is hard to solve the congestion problem of existing road networks and offer support to the formulation of real-time traffic management measures (Lu, Shi, & Yin, 1996).

Therefore, it is necessary to adopt more advanced planning methods and models to describe the dynamic characteristics of travel demand and traffic flow. As more and more research efforts move from conventional trip-based models to activity-based models, the application of ABM in travel demand forecasting has attracted increasing research interests. With better knowledge of Dynamic OD Estimation (DODE)¹ and Dynamic Traffic Assignment (DTA)², we may conduct dynamic analyses for transportation systems.

However, DODE is computationally expensive and fails to reveal the essence of OD generation. Though it is advanced when compared with traditional planning model, DTA still selects the shortest path comparing the total link travel time or normalized travel cost. This theory does not match with human’s heterogeneous choice behaviors, because it is incompatible to commonsense (Banister, 1978). In summary, existing theories have their own shortcomings and insufficiency for integrated evaluation and optimization of various transportation policy, planning scheme, traffic management and control strategies. Therefore, an integrated planning framework that is capable of dealing with different levels of transportation issues and dynamic travel demands is in need to fill the gaps aforementioned.

Transportation systems consist of numerous intelligent agents (e.g., agencies, businesses, households, drivers, and vehicles) that interact with one another on various time scales in urban and regional systems, producing complex system-level patterns, such as congestion, energy consumption, and pollution and carbon emissions.

Agent-Based Modeling (ABM) is an innovative modeling technique that describes a complex system as a collection of autonomous decision making entities dubbed as agents. It focuses on naturalistic (or descriptive) representation of individual behavior and seeks to capture emergent global (or system-wide) patterns resulting from the local interactions and decisions of individual agents (Zhang, 2011). ABM is a bottom-up modeling paradigm, which has significant difference with the traditional modeling paradigm based on equations (Parunak et al., 1998). Traffic systems are large and complex systems that involve a large number of agents (such as drivers, vehicles), and the complex and dynamic nature of the transportation system determines that ABM can be

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¹ DODE that uses road traffic volume to estimate OD matrix is the inverse process of traffic assignment.
² DTA is a model using a dynamic OD as an input, attempting to describe the change of network states over time and interactions with travel demand.
applied to the field of travel demand forecast. The conventional travel demand forecast models are mostly based on the utility maximization theory, which ignores the fact that human beings are of bounded rationality. When choosing certain traffic modes, we will not figure out the exact utility values and compare them, but it’s possible to make choices according to a series of “if-then” rules which are formulated based on former travel experiences and current constraints. So the traditional models do not conform the actual situation to people’s choice behaviors, and can’t simulate a person well enough (Cascetta and Cantarella, 1991; Yang and Zhang, 2009; Cominetti et al., 2010). Compared with the conventional models, ABM can better depict each traffic agent’s decision-making behavior and the interactions among them, thus simulating the entire traffic system roundly and dynamically.

Previous researchers have conducted some meaningful attempts to implant ABM into demand modeling (Horowitz, 1984; Ben-Akiva et al., 1991; Emmerink et al., 1995; Zhang & Levinson, 2004; Arentze & Timmermans, 2005; Zhang et al, 2011). ABM performs more realistically to human behavioural laws. Although previous studies on ABM in transportation mainly focused on demand modelling, it provides a reasonable modelling approach for integrated planning and operations framework.

This paper envisions a coherent dynamic agent-based model that simulates dynamic transportation system as an evolutionary process with an explicit clock for time tracking. It is urgent to develop models and tools that consider fast-changing environment for transportation planning and operations in China’s cities, e.g. fast increasing urban population and land use, variation and evolution in travel demand patterns, vehicle ownership growth, ever-shifting traffic conditions and operational conditions, and emergence of new transportation policies. The dynamic modelling concept and resulting tools will also assist decision-makers in both the public and private sectors to design, assess, and implement adaptive and real-time strategies in archiving transportation planning and operational objectives. Traditional models such as the static four-step demand and traffic models have significant limitations in dynamic planning and operations analysis due to their poor representation of temporal interdependencies in real-world urban systems.

This paper is organized as follows. Section 2 illustrates the preliminary concept of dynamic transportation planning from recurrent and non-recurrent perspectives. Section 3 proposes the simulation-based dynamic transportation planning approach using agent-based modelling, and designs a systematic framework for the dynamic transportation planning and operation platform. Section 4 discusses several key components and elementary features of the platform. Finally, Section 5 draws conclusions and discuss future research.

2. The Concept of Dynamic Transportation Planning and Operations (DTPO)

Dynamic transportation planning and operations (DTPO) is a new method which aims to describe the dynamic characteristics of transportation system from both perspectives of travel demand and supply, characterize temporal changes of traffic flow on the basis of time-dependent travel demand, and achieve the goals of optimizing integrated strategies (e.g. recurrent policy and planning, non-recurrent traffic and travel management) for transportation systems. Different from static transportation planning, the adoption of time variable enables DTPO to better describe dynamic attributes of urban transportation systems. It could provide not only guidelines to the planning and construction of road network, but also proposals to the management and control of transportation systems. In a specific manner, DTPO could be applicable in solving transportation-associated problems in two scenarios: DTPO in recurrent and non-recurrent situations. Features of DTPO in different levels are summarized in Table 1.
Table 1. Features of the dynamic transportation planning and Operations (DTPO) in two scales

<table>
<thead>
<tr>
<th>Perspectives</th>
<th>Factors</th>
<th>Purposes</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recurrent scenarios</td>
<td>Urban changes: land-use patterns, economic growths, population, industrial structure, employment distribution</td>
<td>Describes the dynamic operations of transportation systems during the urban life-cycle, and time dependent attributes of traffic flow</td>
<td>Urban recurrent economic development strategy, comprehensive land-use planning strategy, infrastructure investment proposal, road network optimization program, macroscopic traffic management policy, recurrent dynamic road traffic control scheme, etc.</td>
</tr>
<tr>
<td>Non-recurrent scenarios</td>
<td>Unusual circumstances: holidays, important events, and unprecedented situations</td>
<td>Describes the deviations of traffic demands under unusual circumstances, extreme events; Adapt the policy with time dependent attributes of traffic flow</td>
<td>Developing non-recurrent optimized traffic induced schemes, non-recurrent traffic control schemes, non-recurrent traffic evacuation schemes, emergency repair scheme, etc.</td>
</tr>
</tbody>
</table>

2.1. DTPO in recurrent scenarios

In recurrent scenarios, changes of macroscopic indicators such as urban population, economy, land-use patterns, industrial structure, employment distribution and vehicle ownership can induce dynamic changes in urban travel demands. From a macroscopic perspective, dynamic transportation planning describes the dynamic operations of transportation systems during the whole urban life-cycle. Taking annual statistics as input, we can build up the functional relationship between traffic demand and macroscopic indicators such as population and land-use patterns. They could deduce the changes of traffic demands and obtain dynamic performances of the transportation system in the long term. Because of the large time span, those specific daily deviations of traffic volumes would not be considered as objectives in this paper.

DTPO in recurrent scenarios is closely related to land-use patterns, populations and economic patterns. Hence, the application of this level would mainly concentrate on macro-control transportation policies and schemes, including city’s long-term economic development strategies, comprehensive land-use planning, urban infrastructure investment proposals, road network optimization program, macroscopic traffic management policies and etc.

DTPO in recurrent scenarios operates with a real-time transportation tool that is concerned with the time dependent attributes of daily traffic demands and traffic volumes. Through the means of real-time link data collection and demand forecasting, it obtains the real-time features of traffic flows in order to provide induced and control strategies. Traffic induced scheme is an information-release scheme based on active traffic information, which release accurate and effective traffic information through VMS, broadcasting and GPS systems to induce travellers’ route choice adjustment, ultimately to increase the level of services of road networks. Traffic control is an intersection-control scheme using time dependent traffic volume, including signal time assignment, dynamic all red extension, etc. The real-time tools assist in adapting the optimal planning and operational policies.

2.2. DTPO in non-recurrent scenarios

DTPO in non-recurrent scenarios is mainly concerned with dynamic variations of traffic demands under unusual circumstances or extreme events such as holidays (e.g. Spring Festival, International Labour Day and National Day Holiday), important Events (e.g. 2008 Beijing Olympic Games, 2010 Shanghai World Expo and
2010 Guangzhou Asian Games), and unprecedented situations (e.g. traffic accidents, snow disasters and earthquakes). Applications in the non-recurrent level provide a set of emergency measures through the description and analysis of equilibrium between transportation supplies and travel demands. Under such circumstances, travel demand would burst out in a short period inducing temporal and spatial travel pattern changes, for example, the intercity travel demands would drastically rise during holidays while commuting trips would drop below normal counts.

DTPO in non-recurrent scenarios is inconsistent with changes of traffic demand and travel behaviours under emergency, and achieves the short-term balance between travel supply and demand by developing emergency induced and control schemes. Applications on this level aim at unusual circumstances, such as developing non-recurrent optimized traffic induced schemes that induce on-road travellers to change their routes and relieve the local congestions by releasing active traffic information; developing short-term traffic control schemes that ensure the effective isolation of accident spots through a set of traffic signs like ‘No Entry’, ‘No Turns’, and roadblocks; developing evacuation schemes, including the evacuations of pedestrian, bicycles and mixed motor-vehicles that guarantee the least congestions of traffic flows at each intersection; developing emergency repair scheme and etc.

DTPO in non-recurrent scenarios also operates with real-time transportation tools. It adapts the measures according to real-time data analyses to realize the non-recurrent transportation optimization.

3. Platform of Simulation-Based DTPO

3.1. Simulation-based DTPO approach

As mentioned above, DTPO aims at optimizing macroscopic economic and traffic management policies dynamically based on the objective city’s dynamic travel demand data. Also, DTPO can be viewed as a dynamic approach for transportation planning and traffic control. This characteristic requires visual observations of the performances of the whole system, e.g. before and after policies, network status, control strategies, etc. And should be virtually modified by decision-makers when operating specific planning and optimizing projects.

Based on such features and requirements, this paper proposes a Simulation-based Dynamic Transportation Planning and Operations Approach (SDTPOA). Traffic simulation plays as a traffic analysis tool using simulation models to reflect complex traffic performances (Wang & Zou, 2012). Simulator meets the basic requirements of DTPO, relying on its superiority on computational ability and adjustability of operating parameters. SDTPOA includes five procedures, as shown in Fig. 1.

(1) Dynamic data collection. Since disturbances caused by a city’s development and non-recurrent events (large conferences, natural disasters, etc.) could lead to considerable changes of demand characteristics, dynamic data collection is the fundamental procedure of DTPO. Data mainly consists of:
   • Recurrent data: Data of normal conditions, like population, GDP, land use status, industrial structure, vehicle & bicycle ownership, etc.;
   • Non-recurrent state data: Data and characteristics of non-recurrent events, like large conferences, national sports games, natural disasters and traffic accidents.

(2) Dynamic demand data forecast. Use the demand forecasting model and cities’ dynamic data to produce dynamic travel demand data for simulation.

(3) Traffic simulation. Construct urban road network and related constraints in the simulator, import dynamic demand data and run the traffic simulation. The simulation results include link performances, traveller OD and routes, travel time and distance, etc.

(4) Strategy formulation. According to the simulation results, formulate sustainable urban development strategies (e.g. industry modification, integrated planning, and infrastructure investment) and sustainable transportation system development strategies (e.g. integrating transportation planning, network optimization,
system control and operation). Besides, short-term management schemes, including traffic control, flow drainage and road emergency maintenance for non-recurrent events are also considered.

(5) **Strategy optimization.** Import the formulated strategies as new constraints into the simulator, modify and optimize strategies on the basis of the simulation results until the system performance requirements are satisfied.

![SDTPOA Procedures Diagram](image)

**Fig. 1. The procedures of SDTPA**

### 3.2. Key components

Among all the steps shown in Fig. 1, the most critical steps are travel demand forecast, traffic simulation and strategy optimization. These three key components will be analyzed as follows.

#### 3.2.1 Demand forecast modeling
One key component in DTPO platform is adopting agent-based travel demand model for travel demand forecasting, and integrate the travel demand model with the traffic simulator. It will implement more reasonable simulation results to describe transportation systems.

Currently in China, the methods in response to traffic problems are focusing on supply extension, such as roads widening, constructing viaducts and overpasses. Vehicle ownership and usage rationing is only taken out in large cities such as Beijing and Shanghai (the private vehicle quota system). Without the demand management, travelers just seek the optimal travel behavior without considering enough social cost of their trips and they will change their travel behavior easily, without any penalty of adding the burden of the transportation systems. The huge population in big cities of China makes transportation problems more complicated, as fewer people will behave in an ideally optimal way. So that ABM is more suitable to China’s condition.

In addition, more pedestrians walk along the roadside while they do not obey the traffic rules completely. Pedestrian interference is also frequent on roads, which makes the vehicle system hard to be stable. Thus, the ABM models shall take into consideration of road traffic with more attention to pedestrians.

As more and more subway lines are being constructed in order to initiate public transportation, more construction sites will block roadways and so the platform shall consider this interference as well.

The critical premise of agent-based travel demand modelling is to obtain the main characteristic of people’s travel and driving behaviours by carrying out extensive surveys, then to build an agent-based travel demand model which includes destination choice, route choice, departure time choice and traffic mode choice based on the survey data. In detail, the model includes three aspects:

1. Microscopic individual traveller level: study the travel behaviour of each individual, and then set up search rules and decision rules of travellers based on the survey data, form agent-based travel demand model in microscopic individual traveller level.

2. Macroscopic transportation system level: integrate all the models in microscopic individual traveller level according to the interaction of travellers, then form the agent-based travel demand model in macroscopic transportation system level, including departure time search and decision model, traffic mode selection model and route selection model, and eventually form the dynamic OD matrix and the information of travel mode, departure time and route selection.

3. Agent-based adjusting model: set up travelers’ adjusting rules when stochastic events happen.

3.2.2 Traffic simulation

Traffic simulation is important for the DTPO approach because simulation process can replicate the complex interaction among vehicles, describe spatial-temporal link performance variance and update traveler experiences through iterative manipulation, which is imperative for the DTPO approach. The simulator incorporates demand data and strategy constraints as inputs. After iterative process, the simulation results will reach the convergence criteria, and users could get the link and the whole system performance. Besides, traveler experiences are also available for further calibration and strategy formulation, thus enhancing precision of the DTPO approach and providing useful reference for the next step.

Noteworthy, simulator parameter calibration is crucial for simulation. The discrepancy between Chinese traffic characteristics and western countries makes it difficult to use existing simulators directly, because traffic flow in China are more fixed – bicycles, pedestrians and electric motor cycles occupied a considerable proportion; besides, Chinese agents behave differently from western countries in the system on their choice criteria, traffic regulation compliance degree distribution, etc. Such variances could lead to huge inaccuracy in the modeling process.

3.2.3 Strategy optimization
Step 5 in Fig. 1 is final key component of DTPO. Based on the convergent simulation results and development (operation) strategies, the strategy optimization will set up a single/multi-objective optimization model to evaluate the sustainable transportation system and optimize the formulated planning and operation strategies.

3.3. Requirements of the DTPO platform

The key procedure of DTPO is to construct a DTPO platform that integrates the agent-based model for travel demand forecasting with transportation simulation process as a whole. To build up the DTPO platform framework, we summarize existing representative traffic simulators and compare them with the proposed DTPO platform, see Table 2.

As shown in Table 2, functions of the existing traffic simulators show that they have been able to conduct comprehensive analysis of multi-level, multi-mode, multi-scenario traffic simulations. For example, TransModeler is capable of simulating transportation systems from macroscopic, mesoscopic and microscopic perspectives based on users’ demand. VISSIM is able to model multiple transportation modes including light rail, cars, tricycle, bus, bicycle and pedestrian. DynaMIT and TOPL can simulate the transportation system under variety of scenarios and different stochastic events. However, these existing simulators require demand data, which means there is a gap between demand forecasting and traffic simulation. This problem would be a major impedance of the integrated DTPO process. The exception, TRANSIMS, whose activity-based demand modeling section could be considered as a reference, however, is limited by its GUI, complex modeling process and bewildered parameters settings. Besides, considering transportation system features and traveler characteristics in China, they are more or less inconvenient and inappropriate when directly applying existing simulators in addressing China’s urban transportation issues. Therefore, the DTPO platform that adopts complex traffic conditions of China’s urban transportation systems is imperative.

Table 2: Comparison of the proposed DTPO platform with existing traffic simulators

<table>
<thead>
<tr>
<th>Simulator</th>
<th>System Scale</th>
<th>Features</th>
<th>Applications</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>TransModeler</td>
<td>Macro/Meso/Microscopic</td>
<td>Able to combine with TransCAD; able to implement DTA process; Open Source</td>
<td>Highway and city network management; Ramp, Roundabout and intersection control; Specialized road and simulation; ITS infrastructure</td>
<td>commercial</td>
</tr>
<tr>
<td>DYNUST</td>
<td>Mesoscopic</td>
<td>Able to implement DTA process; could combine VISSIM via DVC</td>
<td>Multi-class traffic simulation; pricing simulation; random events impacts analysis; ITS control strategies</td>
<td>open source</td>
</tr>
<tr>
<td>TRANSIMS</td>
<td>Microscopic</td>
<td>Activity-based demand model; Able to implement DTA process; Open Source</td>
<td>Demand forecast; Transportation planning and operating strategy simulation</td>
<td>open source</td>
</tr>
<tr>
<td>DYNASMART</td>
<td>Mesoscopic</td>
<td>DYNASMART-X, DYNASMART-P</td>
<td>Dynamic OD estimation; Real-time flow drainage and control; Dynamic traffic assignment; Policy accessible Random events, weather variation, road construction and demand fluctuation considered; Ramp control, HOV &amp; HOT lanes</td>
<td>commercial</td>
</tr>
<tr>
<td>DynaMIT</td>
<td>Mesoscopic</td>
<td>DynaMIT, DynaMIT-P</td>
<td>Real-time traffic detection and control; Ramp control; Policy effects fast estimation</td>
<td>commercial</td>
</tr>
<tr>
<td>VISSIM</td>
<td>Microscopic</td>
<td>Able to combine with VISUM; Good GUI Major in use of Highway and Arterials; based on PEMS system</td>
<td>Normal traffic simulation</td>
<td>commercial</td>
</tr>
<tr>
<td>TOPL</td>
<td>Macroscopic</td>
<td></td>
<td>Real-time traffic detection and control; Ramp control; Policy effects fast estimation</td>
<td>commercial</td>
</tr>
</tbody>
</table>
3.4. Agent-based DTPO platform

Each person is tracked in the agent-based model, and his/her spatial knowledge and experiences accumulate over time as he/she makes decisions as a driver, an individual traveler, or as part of a household. Building on this vision, this paper proposes to develop an agent-based approach for driver and traveler behavior modeling with applications for recurrent and non-recurrent transportation systems planning and operations. Dynamic urban land use and socio-economic, dynamic vehicle ownership, dynamic travel demand, and dynamic network traffic will be jointly analyzed with a coherent DTPO platform.

![Agent-based DTPO platform framework](image)

Fig. 2. Agent-based DTPO platform framework
On the basis of advantages of these existing simulators, this paper designs a DTPO platform whose key component modules as well as their interdependencies are summarized in Fig. 2. The data hub module mainly stores collected data and transform them to identifiable formats. Strategies module reflects city macroscopic policies, developing strategies, transportation system planning, operation and control strategies, etc. Based on the basic data and citizen travel decision characteristics survey data, the modeling engine uses an agent-based travel demand model to forecast dynamic travel demands under various circumstances classified into recurrent and non-recurrent conditions. The next step is to import travel demand data into the dynamic traffic network and conduct macro/meso/microscopic traffic simulations. Simulation results will be evaluated and optimized using the optimization module; the iterative process will help the results meet the convergence requirements, and then put into user interface for post processing, where strategies, data and simulation results could be visualized for decision support.

Fig. 3. SDTPOA flow chart under recurrent conditions
Due to various reasons that trigger disturbances in travel demands, the applications of DTPO can be mainly divided into two types: 1) recurrent system dynamic transportation planning and 2) non-recurrent system responses.

Recurrent conditions refer to a city’s regular development and daily transportation performance. Under these conditions, recurrent dynamic urban development, e.g. GDP increase, land use changes, vehicle ownership increase and etc., may lead to system travel demand characteristics changes. The platform imports dynamic demand data to export sustainable economic and transportation system development strategies. The flow chart is shown in Fig. 3.

Non-recurrent conditions refer to circumstances when short-term extreme events or incidents occur. Under these conditions, the platform requires non-recurrent events characteristics and recurrent dynamic demand data, to export short-term and emergency traffic control and management schemes. The flow chart is shown in Fig. 4.

**Fig. 4. SDTPOA flow chart under non-recurrent conditions**
4. Conclusion

With the acceleration of China's urbanization and motorization, traffic problems, such as traffic congestion and traffic accidents, are getting worse and have become an important factor which hinders the healthy development of Chinese cities. Traditional static traffic planning methods are not good at describing the dynamic characteristics of a transportation system. They become increasingly powerless in solving the current traffic problems. On the basis of the existing research, this paper proposes the concept of DTPO, and explains the connotation and application of DTPO in recurrent scenarios and non-recurrent scenarios. In addition, this paper puts forward a simulation-based DTPO method and designs a DTPO platform which integrates agent-based travel demand model and traffic simulation, and explains the functions of each module in detail as well as the operating mechanism of the platform under both recurrent and non-recurrent situations. Furthermore, ABM, which is the key component in DTPO platform, is also introduced. The objective of our future research is to apply ABM to build travel behavior models which are fit for people's travel characteristics in China based on extensive survey data and then set up DTPO platform for practical application which can provide meaningful help to solve the traffic problems in China.

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