A SYSTEM DYNAMICS APPROACH FOR THE IMPACT OF TRANSIT-ORIENTED-DEVELOPMENT AND COVID-19 ON KAOHSIUNG MASS RAPID TRANSIT RIDERSHIP (1076)

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Abstract. TOD reduces private transportation use, promotes public transportation development, and increases ridership. This study examines the Kaohsiung MRT to suggest planning recommendations for each station type. System dynamics are used to simulate the feedback relationship between TOD planning factors and MRT ridership. Results show that all station types positively impact TOD-Design, while TOD-Density is the main factor affecting ridership for "Suburb" and "CBD" stations, and TOD-Diversity for "Residential" stations. The study aims to improve public transportation ridership and provide policy strategies for promoting TOD.

Keywords: transit-oriented development; system dynamics, ridership

1. Background

With Taiwan's push for Transit-Oriented Development (TOD) initiatives, cities aim to integrate people, activities, and public spaces, thereby promoting public transport usage and reducing reliance on private cars. Yet, Kaohsiung's urban development has led to a high-density, low-intensity city center and an Automobile-Oriented Development (AOD) model in emerging areas. Despite the government's TOD efforts and enhancements to metro ridership, the absence of station-specific guidelines has hindered progress and yielded unsatisfactory outcomes. Nonetheless, TOD's primary aim is to effectively reduce the use of private transport. Additionally, it seeks to facilitate the development of public transport to increase ridership (Pan, Li, Shen, & Shi, 2017).

Therefore, this study aims to investigate the main factors affecting passenger traffic at each station of the Kaohsiung MRT, and to provide customized planning suggestions for different station types. Through this study, the TOD strategy for Kaohsiung City can be further optimized. Suggestions and countermeasures for each station will be proposed to better achieve the desired goals of TOD.

The study will examine the impact of TOD planning factors on ridership using the Kaohsiung MRT Red and Orange Line as the empirical area, exploring Density, Diversity, Pedestrian and Bicycle Friendly Design, Destination Accessibility, and Distance. A system dynamic feedback loop will be established to circumvent the limitations of cross-sectional analysis that arise due to insufficient long-term data in multivariate regression methods. The simulation results will guide policy strategies to promote TOD in the future.

- The system dynamically simulates the degree to which changes in the parameters of each factor influence ridership, and it derives appropriate planning policy tools for each type of station.
- The goal of this study is to build scenarios that simulate the impact of changes in the TOD planning elements on its ridership, as well as on the overall population, industry, commerce, and private transport.
- To develop TOD planning guidelines for each type of station.

2. Literature Review

2.1 Relationship between TOD and rapid transit patronage

Transit-oriented development (TOD) can increase public transport ridership through its three elements: Density, Diversity, and Pedestrian Friendly Design (Cervero & Kockelman, 1997). However, TOD can also have negative impacts on environmental quality (Ewing & Cervero, 2001). Studies have shown that applying TOD planning factors, such as the development of urban design around stations, can reduce total trips and vehicle miles traveled, improve air quality, and increase ridership (J. J. Lin & Gau, 2006; Cervero & Kockelman, 1997). TOD planning can also influence changes in behavioral choices and riderships, facilitating its development (Cervero, 2004). The relationship between TOD planning and public transport ridership has been explored in Taipei City, where it was found that ridership is significantly higher in a TOD-compliant urban environment (density, diversity, design). The key factors for success regarding TOD planning on the built environment can reduce the use of private modes of transport (Ewing & Cervero, 2001; J.-J. Lin & Shin, 2008). This study aims to examine the benefits of TOD planning and its dynamic impacts on ridership in order to guide subsequent strategies and to verify hypotheses to be used for simulation (Ewing, Hamidi, & Grace, 2016).

2.2 TOD Planning and Key Factors for Success

Academics have proposed a set of important planning factors for TOD implementation, including the '3D' factors of density, land use diversity, and pedestrian-oriented design (Cervero & Kockelman, 1997). According to Cervero, Sarmiento, Jacoby, Gomez, and Neiman (2009), public transit distance and destination accessibility are also important factors affecting the effectiveness of TOD, thereby forming the '5D' planning factor. The impact and relevance of these 5D planning factors on the ridership of TOD will be investigated later.

•Density

Compact land use density can significantly increase the frequency of public transport system services, which in turn can improve ridership and convenience (Cervero & Kockelman, 1997; Ewing & Cervero, 2017; Cervero et al., 2009). In addition, increased housing density and public facilities around public transport stations may bring additional benefits (Li, Li, Li, Xu, & Qin, 2008; Ratner & Goetz, 2009; Ratner & Goetz, 2013). However, high-density development can lead to a deterioration in environmental quality and give rise to negative issues such as congestion and social injustice (Xia, Zhengwei & Zhang Ye, 2019).

•Diversity of Land use

Mixed residential and commercial uses can promote walking or bicycling to destinations, increase access to public transit, and reduce the use of private transportation. Cervero and Kockelman (1997) found that mixed land use in the San Francisco Bay Area reduced travel demand and increased non-motorised use. Loo et al. (2010) suggested a strong positive correlation between mixed land use and rail transit ridership in Hong Kong. Chen et al. (2011) showed that high building densities and land use diversity promote the use of public transport.

•Design for Pedestrian-Friendly System

Good urban design can provide easier access to destinations and create more friendly and safe spaces for pedestrians, bicyclists, and transit passengers, thereby encouraging the use of public transport (Cervero & Radisch, 1996; Niles & Nelson, 1999). The design of mixed-use street profiles can stimulate the desire to walk, thereby reducing the use of personal transport (Cervero & Kockelman, 1997). Loo et al. (2010) found a positive correlation between mixed-use land use in Hong Kong and rail transit usage. The study also showed that limiting parking space in the city center can improve the quality of public space and the use of public transport (Y.-p. Chen et al., 2011). Pedestrian-oriented urban design can attract business concentration and development, and increase public transport ridership.

•Distance to Mass Transit Stations by Walking

The convenience of transfer systems between different modes of public transport around stations is crucial to enhancing inter-transit transfers. This can increase people's willingness to use public transport (Cheng, Nguyen, & Lau, 2012). As part of this planning factor, the ease of transferring is often assessed by the number of bus stops or bus routes in the vicinity of a rail station.

•*Destination Accessibility*

Improving mobility and accessibility around public transport stations can increase ridership (Cervero et al., 2009; Bai Rendezvous & Liu Renhua, 2014). Accessibility of destinations refers to the ease of reaching services such as kindergartens, schools, colleges, banks, libraries, post offices, hospitals, clinics, restaurants, shopping centers, and hostels from public transport stations. Most studies have used the number or density of these services and establishments as a measure.

2.3 Impact of TOD Factors on Ridership

Previous studies have empirically analyzed the impact of TOD planning on station ridership, primarily focusing on Taipei MRT stations and utilizing different TOD elements (Lin, M. & Shih, 2007). However, these studies have predominantly used cross-sectional data for analysis, lacking long-term validation and policy consideration. Therefore, this study selects Kaohsiung's rail transit stations as the empirical target and uses a systematic dynamic analysis method to study the main factors affecting the ridership of each station, with the goal of increasing public transport ridership.

Dynamics between Urban Transport Systems and Planning Strategies

System Dynamics is a research methodology developed by Jay W. Forrester, a professor at the Massachusetts Institute of Technology, in 1956. It is based on the concept of Information Feedback (Forrester, 1997). Through rigorous quantitative modeling and analysis, it explores the organization and scope of complex systems, the relationship between processes and information within the system, and designs strategies to change system structure and behavior (Chao-Chung Yang, Chang-Hsien Chen, Hsin-Cheng Yeh, & Chiu-Hsien Yeh, 2007).

In transport planning and urban environment studies, system dynamics can be applied to explore the impact of various factors on urban transport systems, such as policy interventions, TOD, environmental factors, tourism, and commuting (Jifeng, Huapu, & Hu, 2008). System dynamics-based analysis can also be used to examine the dynamic effects of TOD redevelopment, light rail station construction, and housing and transport affordability on urban economies.

Our study adopts a systems dynamics approach to construct a model that explores the dynamic relationship between TOD factors and ridership. This approach is aimed at improving the accuracy of system dynamics simulation and proposing guidance for subsequent strategies.

3. Research Design

The research process begins with establishing the motivation of the study, defining the variables that affect the mass transit-oriented traffic according to the previous literature review, and incorporating density, land use diversity, pedestrian-oriented urban design, mass transit interchange distance, and destination accessibility into the system dynamic analysis system, exploring the causal loop of the 5D planning factors within each subsystem, and constructing a system dynamic model for each subsystem. The system dynamic model of each sub-system is then constructed, and the sub-systems are linked by inter-system variables to form a system dynamic model representing TOD planning.

3.1 Data Collection

Based on literature review, we select the 5D variables related to TOD planning practices in Taiwan. Considering the availability of data, we use data from 2011 to 2019, the year before the outbreak of Covid-19, for model calibration. We then simulate the future development of the area surrounding the mass rapid transit stations from 2020 to 2029. In addition, we use the data from the Red Line and Orange Line of the Kaohsiung MRT. Data for population and land use are collected within a 600-meter walking distance using ArcGIS software. Three representative stations from three categories are selected for dynamic simulations.

3.2 Diagrams and Equations for Dynamic Simulation

•*Causal Loop Diagram (CLD)*

The equations used for CLD in the dynamic simulation are mainly calibrated from our collected data and some are adopted from relevant studies.

•*Stock and Flow Diagram (SFD)*

Following the CLD, we elaborate on the SFD to highlight the impact among the key factors in the urban system. A set of specific components for system dynamics is then designed to show all the equations in the above diagrams.

•*Model Calibration and Validation*

In order to simulate future development of other mass rapid transit (MRT) stations in Kaohsiung, we calibrate all the equations and validate our model using statistical tests. We also repeatedly modify our model parameters to reduce the discrepancies between our predictions and the historical data.

4. System Dynamics

4.1 Classification of Kaohsiung MRT Stations

According to previous research (Zhang Xuesheng & Lin Mengyao, 2011), MRT stations should be classified into various groups based on their spatial characteristics and planned using different strategies. Our study applies cluster analysis based on the spatial characteristics and the 5D factors of MRT stations, dividing these stations into three groups. The details of the variables are as follows:

•*MRT Station Ridership*

The annual average number of passengers entering and exiting each station of Kaohsiung MRT in 2019 was used as the sample data to classify the different levels of station use.

•*Housing Land Use*

The land area used for residential purposes within a 600m radius of the Kaohsiung MRT station was used as sample data to group stations by residential density.

•*Commercial Land Use*

The land area used for commercial purposes within a 600m radius of the Kaohsiung MRT station was used as sample data to group stations by levels of commercial use.

•*Industrial Land Use*

The land area used for industrial purposes within a 600m radius of the Kaohsiung MRT station was used as sample data to group stations by levels of industrial use.

•*Diversity Index*

As a measure of diversity, the four categories of residential, commercial, industrial, and other uses within the 600m radius of the Kaohsiung MRT station were used to classify differences in land use diversity. The Shannon-Wiener index was then used to calculate the diversity index, as follows:

$$\mathrm{H} = -\sum_{k=1}^{n} \mathrm{p_k} \ln(\mathrm{p_k}) \quad \text{Eq. 1}$$

P_k: Percentage of land area within spatial boundaries by land use type k

n: Total number of land use categories

4.2 Cluster Analysis

This study employs a two-stage cluster analysis method to classify MRT station samples.

Based on shared attributes among samples, the 37 stations of the Kaohsiung MRT are divided into three clusters: "CBD", "residential core", and "suburban". The characteristics of each station type are as follows:

- *Central Business District*

CBD stations, totaling five, exhibit high MRT ridership, a high proportion of commercial and residential use, and a high diversity index.

- *Residential Core*

Residential core stations, totaling 19, have a high proportion of residential use and the second-highest diversity index.

- *Suburban Area*

Suburban stations, totaling 13, have a high proportion of industrial use but low MRT ridership and a low diversity index.

Our study selects Formosa Station to represent the CBD area, Yanchengpu Station for the residential area, and Weiwuying Station for the suburban area.

4.3 System dynamics models for subsystems

- *Population Subsystem*

The population subsystem uses 'residential population' as a metric, which is influenced by 'natural increase' and 'social increase' flows. The 'in-migration' component of social increase is influenced by the residential use subsystem (Cervero & Kockelman, 1997; Ewing & Cervero, 2017; Cervero et al., 2009). This study defines the main factors influencing in-migration as the average housing price per person and the average number of employment opportunities per person.

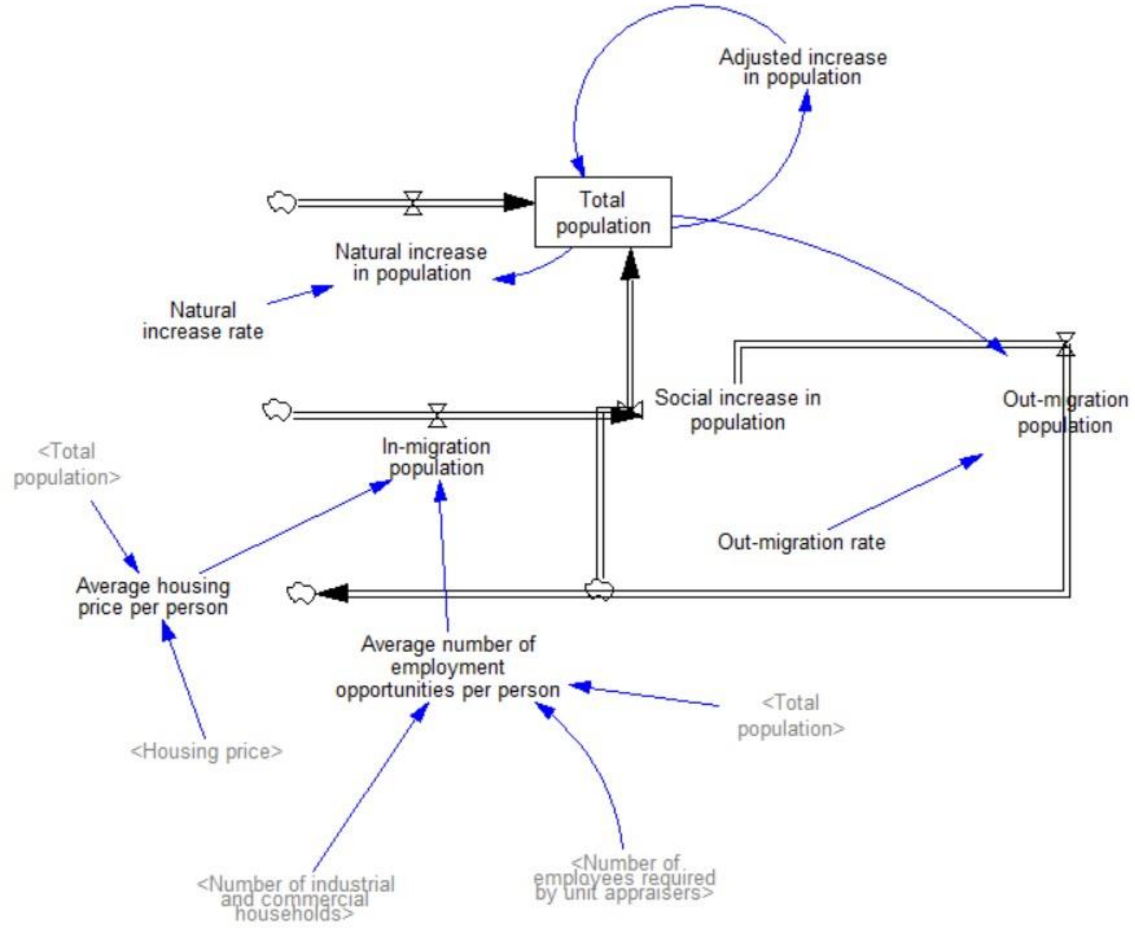


Figure 1. Population subsystem Stock and Flow Diagram

The quantitative model of the population subsystem for Weiwuying MRT station is shown below.

4.4 Resident population

(INTEGER (Social increase + Natural increase))+Adjusted residential population increase/decrease,10642) Eq.2

Description: The initial value is the total population of 10,642 in 2011, sourced from the Socio- Economic Data Service Platform

•Natural increase in population (Unit: Persons/year)

(Total residential population * natural increase rate)/1000 Eq.3

•Social increase in population (Unit: Persons/year)

Incoming population – outgoing population Eq.4

•Incoming population (Persons/year)

INTEGER (1508+(-214244)*average dwelling price per person+(-2127.55)*average employment opportunities per person+(-2.14742e-13)) Eq.5

The regression equation for the in-migration population of zone i in year t: Mi,t = β0 + β1 X1i,t-1 + β2 X2i,t-1 + εit Adjustment after R2 = 0.809

•Moving out of the population (Unit: Persons/year)

INTEGER (Total resident population*Employment rate/1000) Eq.6

•Average residential price per person(Unit: ($10,000/ping)/person)

Total residential price/residential population Eq.7

•Average number of employment opportunities per person (Unit: Number of shops/person)

(Number of industrial and commercial establishments * Number of workers required for the industrial and commercial sector per unit)/Total population living in the area

Eq.8

•Quantitative model table of population subsystem for Yanchengpu MRT Station (Residential Station)

•Total resident population (Unit: Persons)

(INTEGER (social increase in population + natural increase in population)) + adjusting the increase or decrease in residential population, 19546) Eq.9

The initial value is the total population in 2011, 19,546, and the source is the Socioeconomic Information Service Platform.

•Incoming population(Unit: People/year)

2643.09+100053*average residential price per person+(- 4184.64)*average employment opportunities per person+- 7.32649e-13 Eq.10

The regression equation for the in-migration population of zone i in year t: Mi,t =β0 +β1 X1i,t-1 +β2 X2i,t-1 +εit Adjust after R2 = 0.72.

•Quantitative model table of population subsystem for Formosa Boulevard MRT Station (CBD station)

•Total resident population (Unit:People)

(INTEGER (social increase in population + natural increase in population)) + adjusting the increase or decrease in residential population, 41826) Eq.11

The initial value is the total population in 2011, 41,826, and the source is the Socioeconomic Information Service Platform.

•Incoming(Unit:People/year)

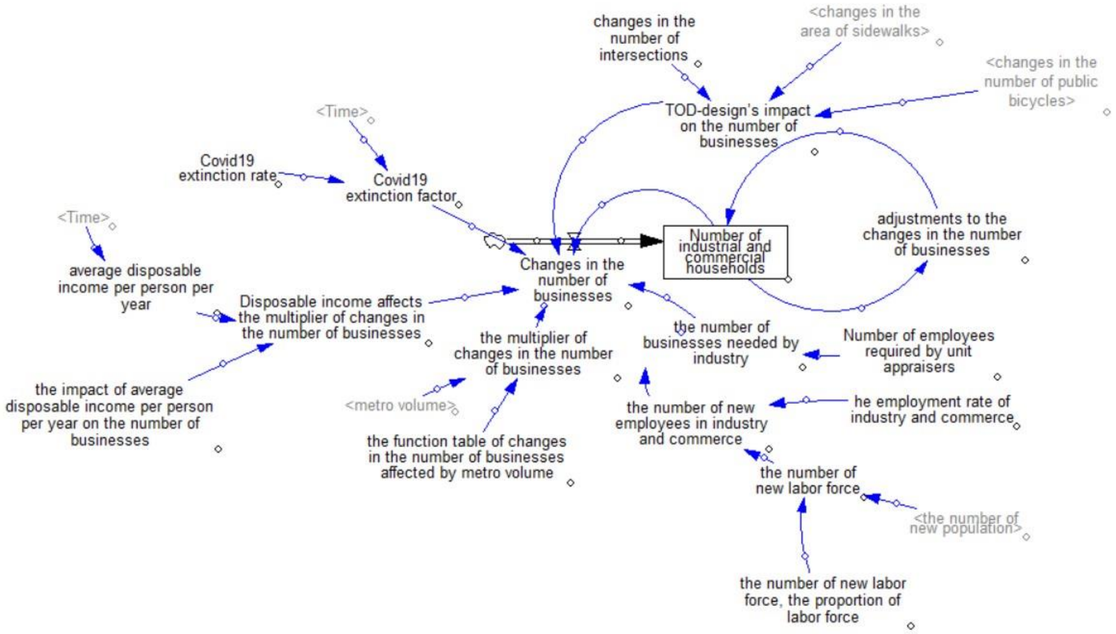
2468.63+(4.92623e+06)*average residential price per person+(2942.98)*average employment opportunities per person+(2.52637e-13) Eq.12

The regression equation for the in-migration population of zone i in year t: Mi,t =β0 +β1 X1i,t-1 +β2 X2i,t-1 +εit Adjust after R2 = 0.67.

•*Commercial Land Use Subsystem*

The residential and commercial subsystem is determined by the number of buildings and households. An increase in population can attract land use benefits, and public transport traffic can boost the density of facilities. This model proposes that the number of commercial and industrial households is influenced by MRT traffic, new inhabitants, and a Covid-19 discount factor. Pedestrian-oriented design can enhance public transport ridership and stimulate business development. This study considers the number of intersections, pavement area, and public bicycles as variables influencing the number of establishments (Cervero & Kockelman, 1997; Ewing & Cervero, 2017; Cervero et al., 2009; Li et al., 2008; Corbett & Zykofsky, 1999).

Increased accessibility to public transport may augment the density of housing and public facilities (Ratner & Goetz, 2013). In this study, the "new housing stock flows" are influenced by MRT ridership, while "reduced housing stock flows" are influenced by the level of housing damage (Chen, 2003; Huang, 2009). The calculation is based on the assumption, following Chen (2003) and Huang (2009), that a dwelling has a life expectancy of 50 years. This is then multiplied by the number of dwelling units, subject to the plot ratio and shelter rate stipulated by the urban plan.



•Quantitative Model of the Residential and Commercial Sub-system of the Weiwuying MRT Station (Suburb Station)

•Number of residential buildings(Unit:Stand)

INTEG ((Number of new residential buildings - number of residential buildings reduced) + increase/decrease in the number of adjusted residential buildings,5146.81) Eq.13

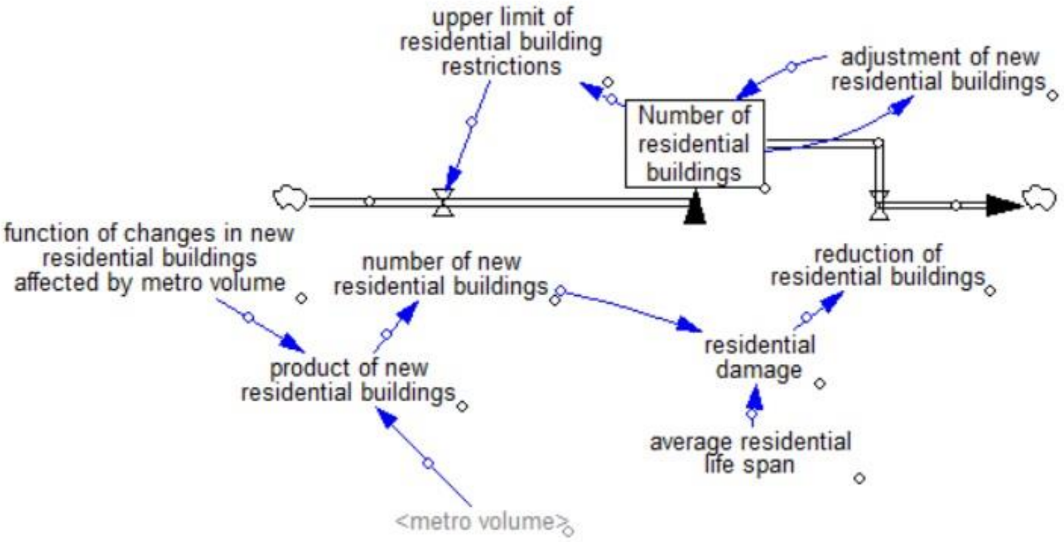


Figure 2.49 Volume flow diagram of the residential and commercial subsystem

The initial value is the number of residential buildings in 2011, 5146

•Number of new residential buildings(Unit: Stands/year)

Number of new residential buildings multiplier*number of residential buildings

•Residential Damage(Unit: Stand)

Number of new residential buildings/average residential life Eq.14

•Number of businessmen(Unit: Number of homes)

Number of industrial and commercial households = INTEG (number of industrial and commercial households increase or decrease + adjust the number of industrial and commercial households increase or decrease,529) Eq.15

The initial value is the number of business establishments in 2011, 529

•Increase or decrease in the number of industrial and commercial households(Unit: Number of homes/year)

(number of industrial and commercial demand + industrial and commercial household change multiplier * industrial and commercial households) * covid19 discount factor + "TOD- Design impact on industrial and commercial households" Eq.16

•The impact of TOD-Design on the number of industrial and commercial households(Unit: Dmnl)

Intersection increase/decrease^0.335622+public bicycle increase/decrease^1.17003+pavement area increase/decrease^0.059772 Eq.17

Historical data regression estimates

•Crossroads additions and reductions(Unit:Dmnl)

207*(increase/decrease ratio)*PULSE(111,8) Eq.18

•Sidewalk area increase or decrease(Unit: Dmnl)

24761.4*(increase/decrease ratio)*PULSE(111,8) Eq.19 Business Demand(Unit:Number of homes)

Number of new industrial and commercial workers/number of workers needed in the industrial and commercial sector Eq.20

•Number of new industrial and commercial workers(Unit: People)

Number of new labour force*Business and industrial employment rat Eq.21

•Number of new labour force(Unit: People)

Number of new population*Proportion of labour force Eq.22

•Quantification model of residential and commercial subsystem of Yanchengpu MRT station (residential core type station)

•Number of residential buildings(Unit: Stand)

INTEG ((Number of new residential buildings - number of reduced residential buildings) + increase or decrease in the number of adjusted residential buildings, 9423.4) Eq.23

The initial value is the number of residential buildings in 2011, 9423

•Number of businessmen(Unit: Number of homes)

Business households = INTEG (Business households increase/decrease +Adjust business households increase/decrease,1890.25) Eq.24

The initial value is the number of business establishments in 2011, 1890.25.

•Crossroads additions and reductions(Dimensionless)

390*(increase/decrease ratio)*PULSE(111,8) Eq.25

•Sidewalk area increase or decrease(Unit:Dimensionless)

23971.8*(increase/decrease ratio)*PULSE(111,8) Eq.26

•Quantitative Model of the Residential and Commercial Subsystem of the Miramar MRT Station (CBD Type Station)

•Number of houses(Unit: Housing Unit)

INTEG ((Number of new dwellings - number of dwellings reduced) + increase/decrease in the number of adjusted dwellings, 13077.2) Eq.27

The initial value is the number of residential buildings in 2011, 13077.2

•Business and Industry(Unit: Number of homes)

Business households = INTEG

(Increase/decrease in business households + increase/decrease in adjusted business households, 5089.77) Eq.28

The initial value is the number of business establishments in 2011, 5089.77

•Crossroads additions and reductions(Unit:Dimensionless)

1090*(increase/decrease ratio)*PULSE(111,8) Eq.29

- Increase or decrease in pavement area(Unit:Dimensionless)

86774.5*(increase/decrease ratio)*PULSE(111,8) Eq.30

- *MRT Subsystem*

MRT ridership is influenced by the number of residential buildings, the population, and private motor vehicles. This study identifies factors affecting MRT traffic as the equilibrium of residential buildings, population density, the number of residential buildings, and motor vehicles. A regression calibration is used to estimate the degree of influence of each factor on MRT traffic.

Kuby et al. (2004) suggest that the utilization of stations as transportation hubs and interchanges, and stations that provide feeder bus routes, can effectively increase ridership. Thus, the addition or subtraction of bus stops becomes an exogenous variable in improving the TOD-Distance element. Cheng et al. (2012) argue that the convenience of walking, cycling, or using public transport to get to the station significantly impacts rail use. Therefore, increasing or decreasing the number of points of interest serves as an exogenous variable for enhancing the TOD-Destination element.

- Quantitative Model of MRT Traffic Subsystem at Wibuying MRT Station (Suburban Type Station)

- MRT Ridership(Unit: People)

MRT ridership attraction + "TOD-Destination on ridership increase/decrease" + "TOD-Distance on ridership effect" Eq.31

- Attractive MRT ridership(Unit:Dimensionless)

1.78837e+06+326798*LN(residential Population density)+197283*LN(residential/commercial balance)+284304*LN(residential buildings/1000)+(-74694.7)*LN(motor vehicles/1000)+57161.1*Waiwuying National Exhibition Centre opening Eq.32

The regression equation for MRT traffic in zone i in year t: Ri,t = β + β01 X1i,t-1 + β2 X2i,t-1 + εit Adjustment after R2 = 0.739

- Balance of housing and business(Housing Unit /Shops)

(Maximum number of commercial/industrial/residential buildings) Eq.33

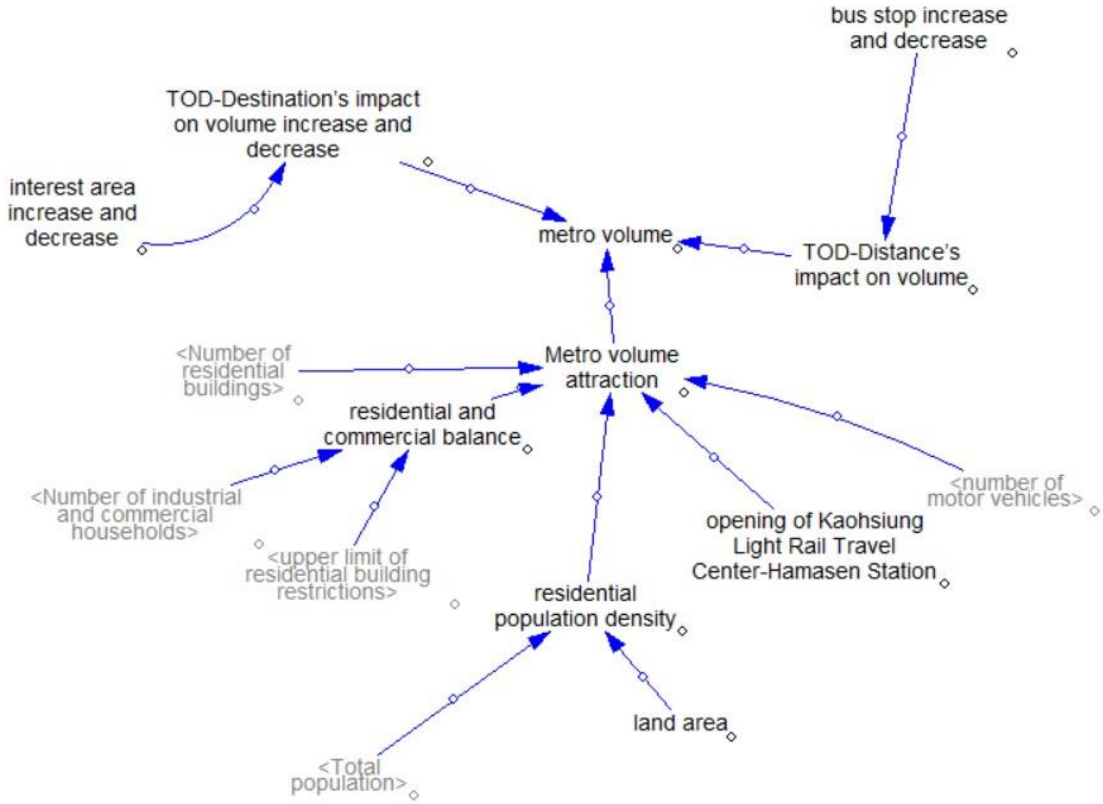


Figure 3.50 Volume flow diagram of the MRT quantum system

- Residential population density(Unit:Persons/square meter)

Total number of inhabitants / Total land area Eq.34

- Increase or decrease in area of interest(Unit:Dimensionless)

(96257.5*(increase/decrease ratio)*PULSE(111,8)) Eq.35

- TOD-Distance impact on ridership(Unit: Dimensionless)

Increase/decrease in bus stops^0.431 Eq.36

Historical data regression estimates

- Increase or decrease in bus stops(Unit: Dimensionless)

111*(Increment/decrement ratio)*PULSE(111,8) Eq.37

- The impact of TOD Destination on traffic growth and decline (Unit: Dimensionless)

Increase or decrease in area of interest^0.02 Eq.38

Historical data regression estimates

- Quantitative Model of MRT Transport System at Yanchengpu MRT Station (Residential Core Type Station)

- Attractive MRT ridership (Unit: Dimensionless)

(-521785)+3.24422e+06*residential and commercial balance+39.754*residential buildings+(-15.9978)*motorized vehicles+(-16133.6)* "Kaohsiung Light Rail Transit Center - Hamasin Station Opened" Eq.39

The regression equation for MRT traffic in zone i in year t: Ri,t = β + β01 X1i,t-1 + β2 X2i,t-1 + εit Adjustment after R2 = 0.44

- Increase or decrease in area of interest(Unit: Dimensionless)

(190769*(increase/decrease ratio)*PULSE(111,8)) Eq.40

- Increase or decrease in bus stops(Unit:Dimensionless)

144*(increase/decrease ratio)*PULSE(111,8) Eq.41

- Quantitative Model of MRT Quantum System at Miramar MRT Station (CBD Station)

- Attractive MRT ridership(Unit: Dimensionless)

(-1.25471e+07)+1.54006e+06*LN

(residential population density)+360269*LN(residential/commercial balance)+4.05396e+06*LN(residential buildings/1000)+(-713958)*LN(motor

vehicles/1000) Eq.42

The regression equation for MRT traffic in zone i in year t: Ri,t = β0 + β1 X1i,t-1 + β2 X2i,t-1 + εit Adjustment after R2 = 0.59

- Increase or decrease in area of interest(Unit:Dimensionless)

(165670 *(increase/decrease ratio)*PULSE(111,8)) Eq.43

- Increase or decrease in bus stops(Unit:Dimensionless)

Increment/decrement ratio)*PULSE(111,8) Eq.44

- *Private Tooling Subsystem*

The private transport subsystem uses motor vehicles as a volume metric, and population and ownership rate as factors for the annual increase (Cervero & Radisch, 1996; Niles & Nelson, 1999). Mixed land use can reduce private transport and encourage active transport. In this study, we consider the balance of households and businesses as a major factor in reducing the annual motor vehicle usage.

The annual reduction in motor vehicles draws from Cervero & Kockelman (1997). This study posits that the annual reduction in the number of motor vehicle trips is influenced by exogenous variables such as the increase or decrease in the number of public bicycles, and the expansion or contraction of pavement area.

•Quantification Model of Private Transport Subsystem at Wibuying MRT Station (Suburban Type Station)

•Annual increase in vehicles(Unit: per year)

Number of new cars + number of new motorbikes Eq.45

•Annual reduction in the number of vehicles(Unit: per year)

Number of motor vehicles*(- Change in the number of motor vehicles multiplied by the balance of households and businesses) + "TOD- Design impact on the number of vehicles" Eq.46

•TOD-Design impact on the number of vehicles(Unit: Dmnl)

Increase/decrease in pavement area ^0.109 + increase/decrease in public cycling ^0.014 Eq.47

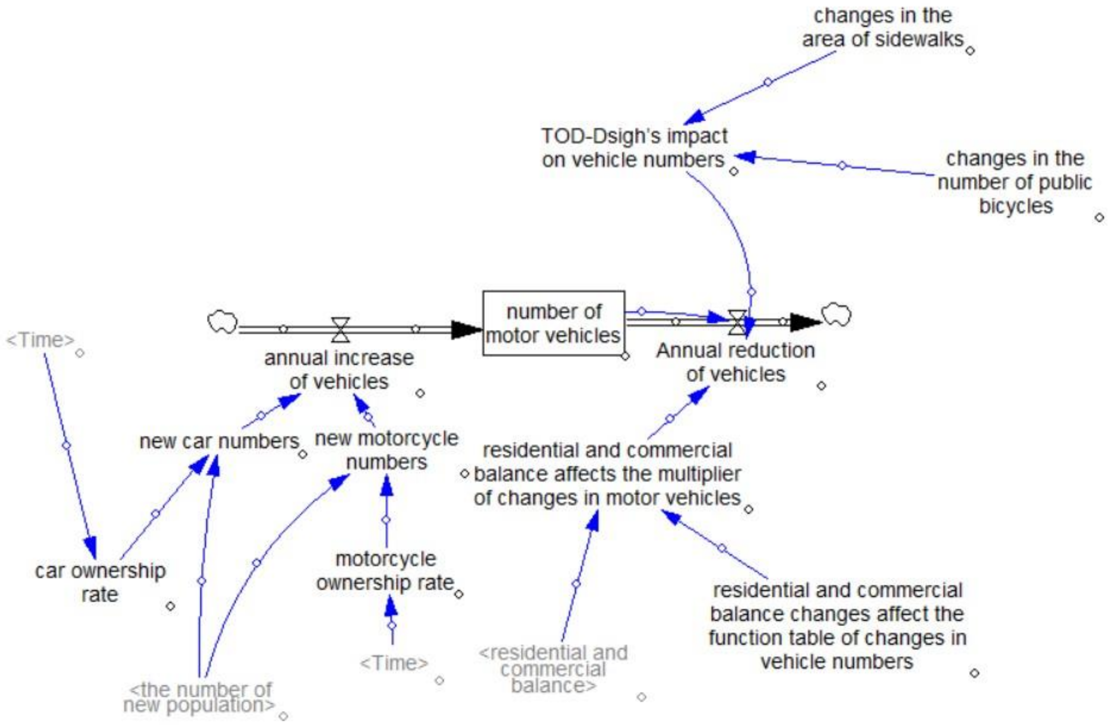


Figure 4. Volume flow diagram of the private transport subsystem

Historical data regression estimates.

•Increase or decrease in public bicycles(Unit: Individual)

7*(increase/decrease ratio)*PULSE(111,8) Eq.48

•Number of new cars(Unit:About)

Car ownership rate * new population Eq.49

•Quantification Model of Private Transport Subsystem at Yanchengpu MRT Station (Residential Station)

•Number of motor vehicles(Unit: About)

Number of motor vehicles = INTEG ((annual increase - annual decrease), 21079.3) Eq.50

The initial value is the number of motor vehicles in 2011, 21079.3

•Increase or decrease in public bicycles(Unit: Individual)

13*(Increment/decrement ratio)*PULSE(111,8) Eq.51

•Quantification Model of Private Transport Subsystem at Miramar MRT Station (CBD Station)

•Number of motor vehicles(Unit: About)

Number of motor vehicles = INTEG ((annual increase in vehicles - annual decrease in vehicles), 45106.7) Eq.52

The initial value is the number of motor vehicles in 2011, 45106.7

•Increase or decrease in public bicycles(Unit: Individual)

28*(Increment/decrement ratio)*PULSE(111,8) Eq.53

5. Model Validation

Once a dynamic model of the system has been established, it's essential to conduct model validation to ensure its accuracy. This is achieved by comparing the data produced by the model with historical data and identifying any discrepancies. Should any variance be detected, the model's structure or parameter relationship should be adjusted to enhance precision. In this study, the simulated values of relevant variables are computed using historical data from 2011-2019 as the foundation for modeling, while actual data serves as the basis for validation.

This study employs four subsystems for volume validation, including total residential population, the number of commercial and industrial households, the number of residential buildings, the number of motor vehicles, and MRT traffic. The simulated data will be compared with historical data, and the Mean Absolute Percentage Error (MAPE) will be calculated to gauge the degree of resemblance by referencing the validation method of Haghshenas et al. The equation is as follows (1). The historical data utilized in this study ranges from 2011 to 2019.

Mean Absolute Percentage Error (MAPE):

MAPE=(1⁄n)Σ|(I_0-I𝑒)⁄(I_0)| ……………………(1)

Ie = system dynamic simulation value

Io = actual (observed) value

5.1 Population Subsystem

The population subsystem uses the "total residential population" volume as the validation variable. Population data within a 600m radius of the MRT station is obtained from the Socio-Economic Data Service Platform's minimum enumeration area data, which is then processed using the area ratio.

•*Weiwuying MRT Station (suburban type station)*

The population of Weiwuying MRT Station was 10,642 in 2011 and 9,858 in 2019, showing a decreasing trend year by year. The population growth rate over the 9-year period is approximately -7.4%, which corresponds to a mean absolute percentage error of 0.0203, indicating that the validity is within the confidence range.

•*Yanchengpu MRT Station (Residentialstation)*

The population of Yanchengpu MRT Station was 19,546 in 2011 and 16,981 in 2019, again showing a decreasing trend year by year. The population growth rate over the 9-year period is approximately -13.1%, which corresponds to a mean absolute percentage error of 0.0048.

•*Miramar MRT Station (CBD station)*

The population of Miramar MRT Station was 41,826 in 2011 and 39,232 in 2019, following a decreasing trend over the years. The population growth rate over the 9-year period is approximately -6.2%, with a mean absolute percentage error of 0.0166, which indicates that the validity is within the confidence range.

The actual number of residents in the areas of Weiwuying MRT Station, Yanchengpu MRT Station, and Miramar MRT Station all show a decreasing trend from 2011 to 2019, with growth rates ranging from -6.2 to -13.1%. The average absolute percentage errors range from 0.0048 to 0.02053, which are all within the confidence range.

5.2 Residential and Commercial Sub-system - Number of Residential Buildings and Commercial andIndustrial Households

The number of residential buildings and the number of commercial and industrial households are used as validation variables in the residential and commercial subsystems. Data on the number of residential buildings is obtained from the Real Estate Information Platform of the Ministry of the Interior, and data on the number of commercial and industrial establishments is obtained from the Minimum Statistical Area (MSA) data of the Socio-Economic Information Service (SES) platform. Both sets of data are scaled to fit the area within a radius of 600m from MRT stations.

•*Weiwuying MRT Station (suburban type station)*

The number of residential buildings in the area of Weiwuying MRT Station was 5,147 in 2011 and increased to 5,694 in 2019, representing a growth rate of approximately 10.6% over the 9-year period. A comparison of the actual and modeled values shows a mean absolute percentage error of 0.0028, indicating that the validity is within the confidence range. The number of commercial establishments in the Weiwuying MRT Station area increased from 529 in 2011 to 571 in 2019, representing a growth rate of about 7.9% over the 9-year period. A comparison of the actual and modeled values shows a mean absolute percentage error of 0.034, which indicates that the validity is within the confidence range.

•*Yanchengpu MRT Station (ResidentialStation)*

In 2011, the number of residential buildings at Yanchengpu MRT Station was 9423, and in 2019, this number rose to 9531, signifying a growth rate of roughly 1.14% over the 9-year span. The mean absolute percentage error, when comparing actual to modeled values, is 0.0091, which indicates a level of validity that falls within the confidence range. The quantity of business establishments at the Yanchengpu MRT Station rose from 1,890 in 2011 to 1,998 in 2019, showing a 5.71% growth rate over the same period. The actual versus simulated values show a mean absolute percentage error of 0.0216, still within the confidence range.

•*Miramar MRT Station (CBD station)*

At the Miramar MRT Station in 2011, there were 13,077 residential buildings, and by 2019, this number is expected to reach 13,590, indicating a growth rate of approximately 3.92% over the 9-year span. The mean absolute percentage error, when comparing actual to modeled values, is 0.00257, which signals a level of validity within the confidence range. The number of business establishments at the Miramar MRT Station was 5090 in 2011, and it is projected to rise to 5518 by 2019, marking an 8.41% growth rate over the same period. The actual versus simulated values show a mean absolute percentage error of 0.01298, also within the confidence range.

From 2011 to 2019, both the number of residential buildings and commercial/industrial households at the three MRT stations have been on a growth trajectory. The growth rate of residential buildings ranged from 1.14 to 10.6, with Weiwuying Station (a suburban station) seeing the highest growth rate, and Yanchengpu Station (a residential core station) the lowest. Commercial and industrial households had a growth rate between 5.71 and 8.41. The mean absolute percentage error of the survey, ranging from 0.0028 to 0.03, fell within the confidence range.

5.3 MRT Transport Sub-system - MRT Ridership

Using "MRT ridership" as the validation variable, the MRT transportation sub-system obtains station ridership information from the Kaohsiung City Statistical Information Service website, based on the annual average number of passengers entering and leaving each station.

•*Weiwuying MRT Station (Suburban)*

In 2011, Weiwuying Station reported 92,942 MRT passengers, and by 2019, this figure is expected to reach 159,462, marking a substantial growth rate of 71.6%. A comparison of actual values with simulated ones shows a significant difference in 2018.

•*Yanchengpu MRT Station (Residential)*

Weiwuying Station had 174,983 MRT passengers in 2011, and by 2019, this figure is anticipated to rise to 271,583, an increase of approximately 55.2%. The simulated value is slightly lower than the actual value prior to 2016 and slightly higher after 2017, presumably due to the inclusion of a dummy variable accounting for the completion of the MRT Light Rail.

•*Miramar MRT Station (CBD)*

In 2011, Weiwuying Station registered 356,875 MRT journeys, and by 2019, this number is expected to reach 557,439, signifying a notable growth rate of 56.2%. When comparing actual values to simulated ones, the difference is relatively large in 2019, presumably because the model incorporates adjustments made due to the Covid epidemic's impact on the CBD station's traffic.

From 2011 to 2019, all three MRT stations have seen significant increases in MRT ridership, with growth rates ranging from 55% to 72%. The model values for Weiwuying and Yanchengpu MRT stations include dummy variables accounting for the impact of large-scale construction projects on riderships. For Miramar MRT station, the model also considers the effects of the Covid epidemic on CBD station traffic. The mean absolute percentage errors range from 0.03 to 0.09, all falling within the confidence range.

5.4 Private conveyance sub-system - number of motor vehicles

The private conveyance sub-system uses the "motor vehicle count" volume as the validation variable. Data on the number of motor vehicles within a 600m radius from the MRT stations is obtained from the General Bureau of Roads, Ministry of Transport's motor vehicle register, and processed in relation to the population.

•*Weiwuying MRT Station (Suburban)*

Weiwuying MRT Station reported 11,477 motor vehicles in 2011 and 9,963 in 2019, showing a decreasing trend year after year. This indicates a growth rate of -15.2% over the 9-year period. The comparison of actual to simulated values shows a relatively large difference from 2013 to 2015. However, the mean absolute percentage error is 0.03019, demonstrating that the validity is still within the confidence range.

•*Yanchengpu MRT Station (Residential)*

The number of motor vehicles at Yanchengpu MRT Station was 21,079 in 2011 and dropped to 17,162 in 2019. The year-after-year decrease suggests a growth rate of -18.6% over the 9-year period. When comparing the actual to modeled values, the mean absolute percentage error is 0.07356, indicating that the validity is still within the confidence range.

•*Amar MRT Station (CBD)*

The Miramar MRT Station reported 45,107 motor vehicles in 2011, and by 2019, this figure is projected to drop to 39,651. The year-on-year decrease implies a growth rate of -12.1% over the 9-year span. When comparing the actual values to the simulated ones, the latter are consistently higher than the former, but the mean absolute percentage error is 0.0577, indicating that the validity is still within the confidence range.

From 2011 to 2019, the number of motor vehicles at all three MRT stations showed a decreasing trend, with the growth rate ranging from -12 to -19. The mean absolute percentage error of the data ranges from 0.03 to 0.08, falling within the confidence range.

The results of model validation reveal that the mean absolute percentage error across the three models ranges from 0.002 to 0.094, which indicates an error of less than 10% and therefore falls within the confidence range.

6. Conclusion and Discussion

This study investigates the primary factors influencing ridership at MRT stations in Kaohsiung, focusing on TOD density, diversity, pedestrian/cyclist-friendly design, interchange convenience, and destination accessibility. Using system dynamic analysis and historical data from 2011 to 2019, a dynamic model is developed. Kaohsiung MRT is categorized into CBD, residential core, and suburban types based on ridership, residential, commercial, industrial zones, and land use diversity.

7. Limitations and suggestions for research.

This study employs system dynamics, and due to data and scale limitations, acknowledges the influence of exogenous variables. The variability of individual stations may not be fully accounted for. Recommendations for future research include improved data collection, incorporation of external factors, and sensitivity analysis to identify significant variables. These limitations may result in discrepancies between the study's findings and reality.

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