Proceedings of the Eastern Asia Society for Transportation Studies, Vol. 5, pp. 907 - 918, 2005

SYSTEM OPTIMUM FRAMEWORK FOR EVALUATION AND EFFICIENCY OF ROAD NETWORK

L. Bambang Budi PRASETYO
Lecturer,
Department of Civil Engineering,
Institut Teknologi dan Sains Bandung (ITSB)
Jl. Ir. H. Juanda 254 Bandung
Tel./Facs. +62-22-250 03 79
e-mail: lbbp@bdg.centrin.net.id

Muhamad ISNAENI
Researcher,
Department of Civil Engineering,
Institut Teknologi Bandung (ITB)
Gd. Lab. Tek. I Lt. 2, Jl. Ganesha 10 Bandung
Tel./Facs. +62-22-250 23 50
e-mail: isnaeni@trans.si.itb.ac.id

Abstract. Road network system development in Indonesia, until now, always constrain with available budget limit. This condition, investment on road network should be done efficiently using priority scale commitment, depend on problem urgent level and expectation of benefit value.

Right now, generally, performance of road network analysis has been done using user equilibrium (UE) methods; with assume that in along time period a driver will make a best route choice depend on his perception where results his minimum cost. On road network optimality framework, equilibrium method was not capable to give description how efficient a plan of handling schema. Consequently, result of recommendation wasn't optimum solution for handle this problem. One alternative of assignment models that was capable to give indication of efficiency level for a road network use is a system optimum (SO) method. System optimum framework was based on assume that on road network, there is a route choice system solution with a minimum cost system. Using this method will find critical point and efficiency level of a road network use.

System optimum procedures was tested and applied on artificial network and real network of freight transport in Java Island. In artificial case, it was found that SO method is more efficient than UE method. SO method gives efficiency of 8.69% compared to UE method. In real case of freight network in Java Island, it was found that rail expansion is more beneficial than road expansion. Network improvement through rail expansion gives benefit of 7.11% compared to the do-nothing case, while road only 0.5% relative to base condition.

Recommendation and result of this study was useful for road network performance evaluation and to arrange step by step of problem solving of right now and tomorrow cases.

Key Words: *system optimum, equilibrium, efficiency, road investment*

1. INTRODUCTION

In the transport network analysis, especially in road network, the equilibrium approach usually used to reproduce traffic flow. Traffic flow reproduction will achieve distribution of traffic flow on each link, which can be used to analyze and to predict the solution of future transport problem.

Using the equilibrium approach, was named as *predict* and *provide* context, exactly has basic weakness, e.g. part of road network system which make inefficient and how many inefficient condition was caused. The equilibrium approach assumes that in along time period a driver will make a best route choice depend on his perception where results his minimum cost. This condition will over assign on the primary road that caused by unbalance of route competitive level in the network.

The hierarchy system of road network system was classifying road network based on capacity and function. Therefore, the system can achieve an efficient traffic movement. The efficiency was depending on road hierarchy plan and continuity of link in the same hierarchy system. Based on the concept of efficiency that was need an approach to check or test the efficiency level of road network and where the critical nodes in the road network system.

One alternative of assignment models that was capable to give indication of efficiency level for a road network use is a system optimum (SO) method. System optimum framework was based on assume that on road network, there is a route choice system solution with a minimum cost system. Using this method will find critical point and efficiency level of a road network use.

This paper will give the simply illustration about the both assignment models (equilibrium and system optimum), and review basic theory of those models. This paper completed with the model's implementation on artificial and real network cases, so it can give illustration practically for the both models.

2. EQUILIBRIUM METHOD

The equilibrium analysis was adapting road behavior into analog relationship between travel demand and network capacity as market economic mechanism. In this relation, demand function will be cross with supply function in a node as equilibrium result of trade off between the both curves that name as equilibrium node. In the equilibrium approach, as simply, relation between the both curves can be shown in **Figure 1**.

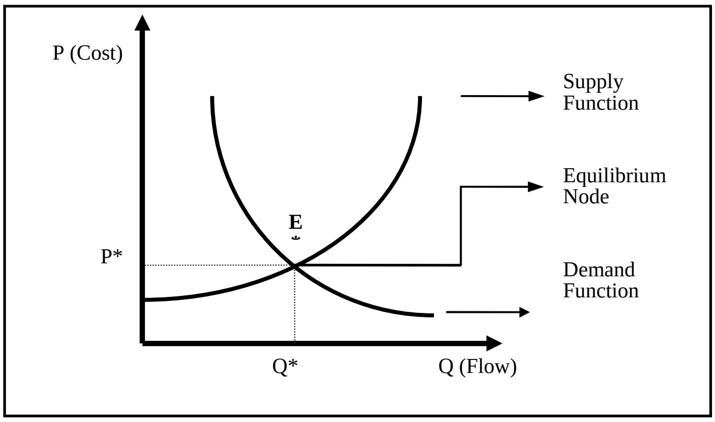

Figure 1. Equilibrium Curve of Demand and Supply *(Source: Sheffi, 1985)*

Figure 1 show that in the network condition, there are equilibrium node E*(Q*, P*) as long term system solution, where Q* and P* were flow and cost of the system.

The equilibrium solution can obtained using two approaches, e.g. behaviorally use user equilibrium approach and normatively use system optimum approach. The system optimum solution may have different result with user equilibrium solution. However, in the efficient road network will achieved the same result between the both approaches. The efficiency, in the context of modeling, was obtained from different ratio of system cost between the both approaches.

2.1 User Equilibrium (UE)

Wardrop (1952) assuming that on all parts of the network, all drivers have an identical perception of cost, proposed principles of route choice in accordance with the two codes of behaviour as follows:

1. The costs on all routes used between any given pair of end poitns are equal and not greater than the cost experienced by a single vehicle on any unused route between them.
2. The average journey cost over all routes used is the minimum possible.

It is generally considered that in practice Wardrop's first principle is the more likely basis for network equilibrium. Similarly, most theoretical work has attempted to produce solutions in accordance with this principle, subject usually to additional constraints.

Beckmann et al. (1956) showed that, assuming that the cost on any link *a* is a function of the flow on link *a* only, i.e.:

$$C_a = c_a(V_a) \tag{1}$$

And that the $c_a(V_a)$ are increasing functions, then the flows V_a satisfying Wardrop's first principle are unique and are the same as those which:

$$\text{minimize} \quad Z = \sum_a \int_0^{V_a} c_a(v)\,dv \tag{2}$$

If the requirement, that $c_a(V_a)$ is an increasing function of V_a is relaxed to allow it to be a non-decreasing function, then the c_a remain unique but the V_a may not be.

2.2 System Optimum (SO)

A solution satisfying Wardrop's second principle is unlikely because of its requirement that drivers should sacrifice self-interest for the common good. However, such a solution provides the minimum value for the total costs available under the specified conditions and is a useful benchmark for comparison purposes.

A system optimum solution is obtained by:

$$\text{minimize} \ C = \sum_{id} \sum_{pid} V_{pid} c_{pid} \tag{3}$$

where: p_{id} = a path from i to d
V_{pid} = the flow from i to d on path p_{id}
C_{pid} = the cost in path p_{id}

One way to solve the SO routing problem can be described as follows by introducing the marginal cost of travel:

$$c_a'(V_a) = c_a V_a + V_a \left[\frac{dc_a}{dV_a} \right] \tag{4}$$

where dc_a/dV_a is the differential of $c_a(V_a)$ with respect to V_a, and substituting c_a' for c_a in Z in equation (2), the system optimum solution may be obtained by minimizing Z provided that

$c_a'(V_a)$ is non-decreasing.

3. LINK COST FUNCTION

In the development of road network system model, link road performance has presented by link capacity and relation between travel cost and link flow. Link flow cost function usually integrated from link speed-flow curve (Ca(v)) as shown in **Figure 2** below.

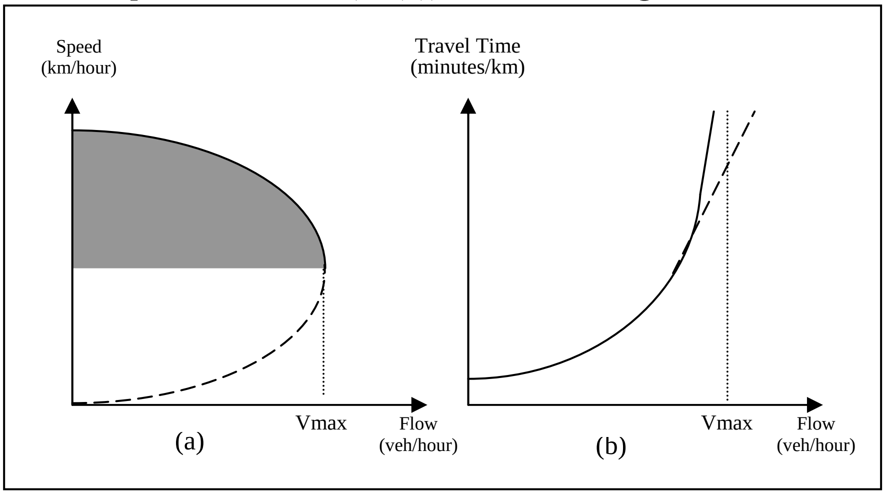

Figure 2. Speed-Flow and Travel Time-Flow Relation Curve *(**Source:** Ortuzar dan Willumsen, 1990)*

In term of speed-flow relation, as shown in Figure 2(a) upper, speed will be decrease follows by increasing of flows. Decreasing of speed will be more higher if the link's flow at capacity. Maximum link's flow was at the capacity and if flow more than capacity will be cause unstable condition with the lowest flow and speed.

For practically of assignment models, speed-flow relation curve usually will be changed to cost-flow relation curve as depict at Figure 2(b) upper. In that figure, dust line was representative condition of flow more than capacity. But, in term of over capacity road network assignment model was need a function which could estimate link's travel time for over capacity link.

In context of develop of road network system model in Indonesia, cost-flow function model usually based on recommended curve by IHCM (Indonesian Highway Capacity Manual) which was got from empirically approach of survey data using Single Regime model as follows:

$$V = FV * [\ 1 - (D/Dj)^{\,l-1}\ ]^{\,1/(l-m)} \qquad (5)$$

$$Do/Dj = [\ (1 - m) / (l - m)\ ]^{\,1/(l-m)} \qquad (6)$$

where FV is *free-flow speed* (km/hour), D is density (smp/hour) was counted in units of Q/C with D_0 and D_j as density at capacity and at over capacity condition. *l* and *m* was constant which was got from model calibration result with using traffic count data surveys.

This needs to note which the Single Regime model was valid for under link's capacity condition only ($Q/C \leq 1$). So, for assignment of road network with $Q/C \geq 1$ was needed assume that cost-flow function was follow the other models.

The main weakness of speed-flow curve function on Single Regime model was to get actual *l* and *m* constant which has needed continue survey result data. This condition was impossible done on this research.

For simplify conversion of the Single Regime function into SATURN's[1] speed-flow function format, was used as tools on the simulation, was done approach at typical of link's speed-flow based on IHCM module, especially on urban road network module as follows equation:

$$V \cong 0{,}5\ Vo\ [\ 1 + (\ 1 - D/S\ )^{0{,}5}\ ] \qquad (7)$$

where V = link speed on flow equal D and Vo = free flow speed, and S = link capacity. Using that equation can explain that on flow at capacity, link speed equal a half of free flow speed condition.

So that, cost-flow curve was got from similar condition as IHCM. Where on IHCM condition, field survey data has been analysed with Single Regime model was been as basic for define typical speed-flow curve of urban road network in Indonesia. The typical curve was published on IHCM chapter 5 about Urban Road STEP D-2: SPEED AND TRAVEL TIME which implement that on capacity condition, speed will be equal a half from the free flow condition.

In SATURN, link cost function was illustrated as universal equation, which that can accommodate all type of link cost function depend on characteristic in each country. Generally, link cost function can be formulated as follows:

$$t = t_0 + a\ V^n \qquad \text{for } V < C \qquad (8)$$

$$t = tc + (V-C)/C \qquad \text{for } V > C \qquad (9)$$

where: t = travel time; t_0 = travel time on free flow condition; C = capacity; V = link flow; a, n = constants.

4. IMPLEMENTATION OF MODELING PROCEDURE

Modeling procedure, as previously discussed, was examined and tested on two networks, i.e. hypothetical network and real network of Java Island.

4.1. Implementation on Artificial Network

In this section, equilibrium method was examined and tested on an hypothetical network. This applied has reason to have comparison between user equilibrium (UE) method and system optimum (SO) method. Equilibrium solution, UE and SO, was solved by using procedures available in SATURN package software.

An hypothetical network that consist two parallel route (1-2-5 and 3-4-5) with two cross route (1-3 and 2-4). Demand was is transported from two origins A, B to one destination C, as displayed in **Figure 3**. The two origin-destination pair, A-C and B-C, has a demand of 100 vehicles.

[1] *SATURN: Simulation and Assignment of Traffic to Urban Road Networks, Institute of Transport Studies, University of Leeds, UK.*

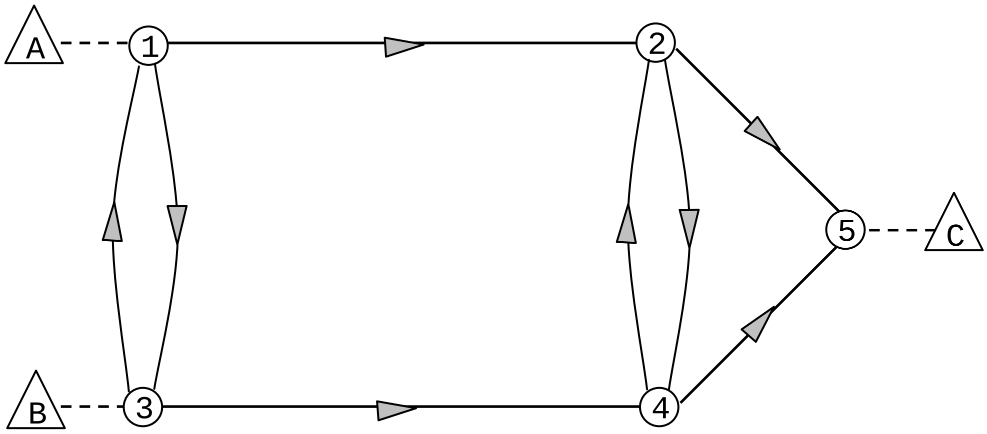

Figure 3. Artificial Network

The link characteristics of hypothetical network are shown in **Table 1**. The parallel route at upper route and lower route has a same characteristic, except for one link, i.e. 2-5 has better link characteristic.

Table 1. Link Characteristic of Artificial Network

Link	Free Flow Time (to)	Time at Capacity (tcap)	Capacity	Power (n)
1 – 2	25	40	150	6
1 – 3*	5	12	60	3
2 – 5	10	20	180	5
2 – 4*	5	12	60	3
3 – 4	25	40	150	6
4 – 5	25	40	150	6

Note: * 2 (two) ways

The equilibrium solution for the hypothetical network are summarized in **Table 2**, together with the benefits that may be available if optimal control is put in place. From **Table 2** can be seen that under SO conditions there are 8,69% benefits compare with UE conditions. This conditions can be achieve with optimal control is put in hypothetical network.

Table 2. Equilibrium Solution on Hypothetical Network

	Total Cost
User Equilibrium **(UE)**	9589,94 veh.sec/hour
System Optimum **(SO)**	8756,45 veh.sec/hour
Benefit	**8,69%**

Figure 4 depicts the flow pattern under both UE and SO conditions for hypothetical network. It can be seen that in order to achieve SO routing it is necessary to divert some trips from upper route to lower route. The divert trips especially for demand from origin B. This yields a benefit of 8,69% relative to the UE condition.

It can be seen that significantly traffic flow assignment differences will be available if comparable between UE and SO, on the last link to C, i.e. link 2-5 and 4-5 with 40,36 vehicle change direction form link 2-5 to link 4-5. It indicated that critical point was result inefficiency on this network be located in unbalance of competitive level between link 2-4 and link 4-5.

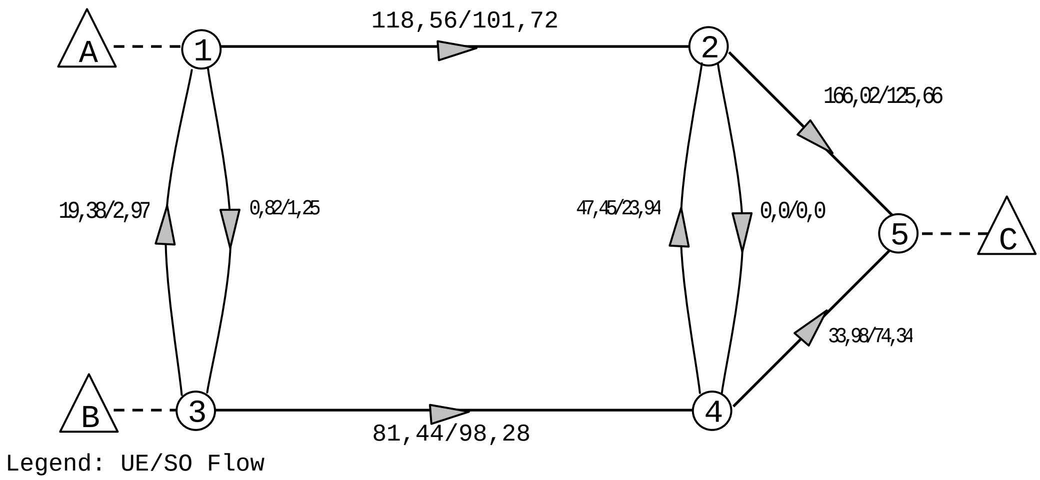

Figure 4. UE and SO Flow Pattern on Artificial Network

As simple illustration for the artificial network system above, the best orientation link capacity improvement scheme was on link 4-5 with reason to make balance competitive level of usage another link, i.e. link 2-5. To minimized investment cost, optimality also done with traffic management scheme which diverted trip from zone A and zone B to zone C with flow pattern similar an optimal condition as result of SO method.

This recommendation has a contradictive result between SO and UE method. If the approach only based on UE method, the recommendation only concentrate in link 2-5 problem. Of course, inefficiency was become, in term of systematically network optimality analysis.

From the result of equilibrium method, UE and SO, in artificial network above, it was created some useful concept or idea for road network development planning, urban or interurban road network. The result above shows that flow pattern using SO method achieve more optimal solution compare with UE method.

Theoretically, UE solution may be have same result with SO solution. In this case, the existing road network was on optimal condition, where the network configuration, in term of capacity share and performance of route competition, was efficiently configuration.

Actually, development of optimum network in an area was impossible mission, because optimal in this context always limited on given condition, e.g. demand and supply. It’s mean that if there are intervention on demand or supply, optimum result as trade off between supply versus demand will on the different condition.

The possible usage of SO approach was on problem solution of road network system, where policy or investment propose can be checked the effect of road network performance improvement. In benefit cost evaluation context of road network system management, SO approach can used to minimize investment cost, where the optimality solution can be done without do something physically. Optimality can achieved using flow control; in the reality can done using traffic management more efficient and effective. Some implementation of traffic management, i.e.: traffic direction management, road pricing, minimum passenger constrain, etc.

However, SO method will give plus value, indicator and control, for evaluation of road network performance. As indicator, the flow pattern were achieved from SO method will give guidance for planner, benefit, in term total of system cost, relatively based on UE method; it is usually used to achieve solution for road network transportation planning. As control, the planner can apply the traffic management scheme exactly and rightly, to achieve flow pattern as resulted by SO method.

With applying SO method as indicator and control, can achieved efficiency, especially in term of investment cost to get the better road network performance. The latest studies always base on UE method approach, and as the solution always suggest widening for road with Q/C $\geq$ 1. In the other word, SO method was use to show optimality probability of road network system, also give better recommendation in investment efficiency and road network system management policy.

4.2. Implementation on Real Network of Java Island

Prasetyo (1999), in his research, was implemented SO and UE method for intermodal transfer on freight transport network. Java Island network has been chosen as case study. Scenario do something A was applied to road improvement case, and Scenario do something B was applied to double track development on rail road.

The study area (Java Island) is divided into smaller areas called zones. The zoning system considers the availability of database for easier modelling. It was decided to use the administrative boundary as a zoning base. There are 78 Kabupatens and 26 Kotamadyas in Java Island. By grouping a Kotamadya to the nearest Kabupaten as one zone, and according to their development area (Wilayah Pengembangan/WP), the number of zones become 20, as displayed in **Table 3**.

Table 3. Zoning System in Java Island

No.	Zone Code	Kabupaten/Kota (Zones)	Kabupaten/Kota Region (Zone Group)
1	101	Jakarta and Buffer of DKI	Jakarta, Jakarta Selatan, Jakarta Timur, Jakarta Pusat, Jakarta Barat, Jakarta Utara, Unknown Jakarta, Purwakarta, Karawang, Bekasi, Tangerang
2	102	Merak	Serang, Pandegelang, Lebak, Rangkasbitung
3	103	Cirebon	Kuningan, Kab/Kod Cirebon, Majalengka, Indramayu
4	104	Bopunjur	Kab/Kod Bogor, Cianjur, Kab/Kod Sukabumi
5	105	Cekungan Bandung	Kab/Kod Bandung, Subang, Sumedang
6	106	Ciamis	Garut, Tasikmalaya, Ciamis
7	201	Subosuko	Boyolali, Klaten, Sukoharjo, Wonogiri, Karanganyar, Sragen, Kod Surakarta
8	202	Semarang-Demak (Kedungsepur)	Demak, Kab/Kod Semarang, Kendal, Kod Salatiga, Grobogan
9	203	Bregas	Batang, Kab/Kod Tegal , Brebes, Kab/Kod Pekalongan, Pemalang
10	204	Karesidenan Pati	Blora, Rembang, Pati, Kudus, Jepara
11	205	Purwokerto	Banyumas, Purbalingga, Banjarnegara, Cilacap
12	206	Kedu	Kebumen, Kab/Kod Magelang, Purworejo, Temanggung, Wonosobo
13	207	D.I. Yogyakarta	Bantul, Sleman, Yogyakarta, Kulon Progo, Gunung Kidul
14	301	Gerbangkertosusila	Sidoarjo,, Kab/Kod Mojokerto, Jombang, Lamongan, Gresik, Bangkalan, Sampang, Pamekasan, Sumenep, Kod Surabaya
15	302	Probolinggo-Pasuruan	Kab/Kod Probolinggo, Pasuruan, Lumajang, Kab/Kod Pasuruan, Kab/Kod Malang
16	303	Bojonegoro	Bojonegoro, Tuban
17	304	Kediri-Tulung Agung-Blitar	Trenggalek, Tulungagung, Kab/Kod Blitar, Kab/Kod Kediri
18	305	Situbondo-Bondowoso-Jember	Jember, Bondowoso, Situbondo
19	306	Madiun	Pacitan, Ponorogo, Nganjuk, Kab/Kod Madiun, Magetan, Ngawi
20	307	Banyuwangi	Banyuwangi

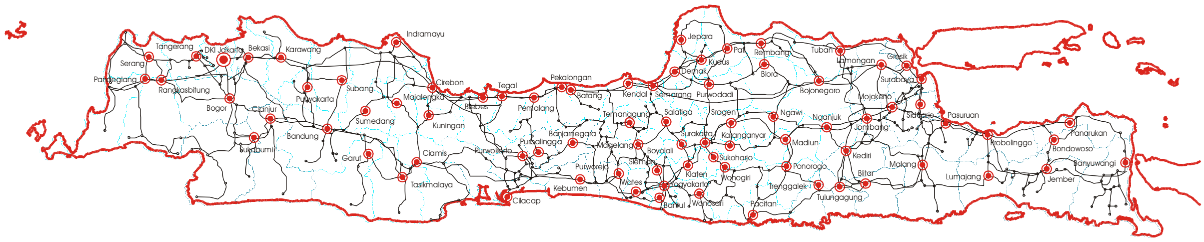

Figure 5. Road Network of Java Island

Figure 5 depicts a land transport network in Java Island, Indonesia. In this study only land transport (road and rail) were considered, as a limitation to the implementation and analysis stage. In the base condition road was categorized depending on its function for carrying freight transport. First category is primary route, i.e. PANTURA (Pantai Utara) or the Java north coast corridor. Second category is secondary route, i.e. 'JALUR SELATAN' or south corridor and 'JALUR TENGAH' or middle corridor. And third category is the alternative routes.

4.2.1. Do Nothing Case/Base Case

In this case, it was evaluated existing condition of multimodal freight transport network in Java Island using UE (User Equilibrium) and SO (System Optimum) method. In this case only land transport (road and rail) were considered.

The equilibrium solutions for the existing Java multimodal network are summarized in **Table 4**, together with the benefits that may be available if optimal control is put in place.

From **Table 4** can be seen that, when comparing assignment results of UE and SO, the SO routing results in a 5.19% of road mode usage, in terms of ton-km, diverting to rail. The SO condition yields a benefit of 2% of the total transport cost relative to the base UE condition.

Table 4. Equilibrium Solutions for the Java Network - Base Case

	JAVA NETWORK – BASE CASE				
	Cost (ton.hr.)	**Road Usage**		**Rail Usage**	
		ton.km	**%**	**ton.km**	**%**
User Equilibrium	1457680	9394799	39,78	14221084	60,22
System Optimum	1428558	8410471	34,59	15904420	65,41
Benefit	**2,00%**				

Figure 6 depicts the pattern under UE condition for the Java network base case. It can be seen that 'PANTURA' and 'JALUR SELATAN' were most used.

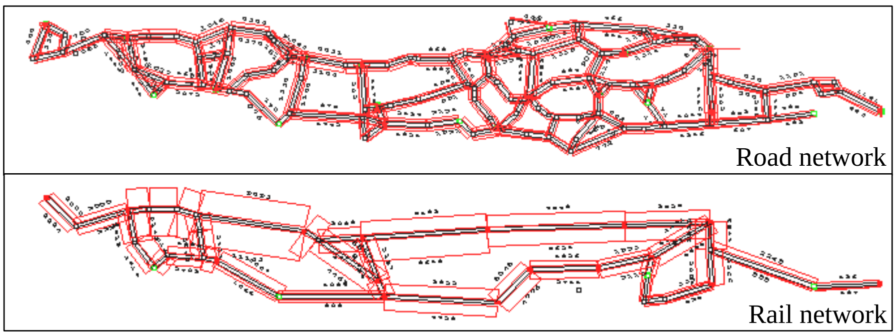

Figure 6. Flow Pattern (Base Condition)

4.2.2. Do Something Case

In the do something condition infrastructure investment was applied on road or rail modes, and potential savings were compared between road and rail modes.

A. Road Investment – Do Something A

Road investment was represented through improvements on some road links in the study area, as can be seen in **Table 5**.

Table 5. Road Improvement - Do Something A

No.	Link Description	Category Improvement
1.	Cileunyi-Nagrek-Tasikmalaya-Ciamis-Wangon	2 to be 1
2.	Yogyakarta-Klaten-Surakarta-Sragen-Ngawi	2 to be 1
3.	Ngawi-Nganjuk-Jombang-Mojokerto-Surabaya	2 to be 1
4.	Semarang-Godong-Purwodadi-Blora-Bojonegoro-Babat	3 to be 2
5.	Yogyakarta-Wonosari-Pacitan-Trenggalek-Tulungagung-Blitar	3 to be 2

B. Railroad Investment – Do Something B

The rail investment scenario was represented with double track rail developments, as can be seen in **Table 6**.

Table 6. *Double Track* Rail Development – *Do Something* B

No.	Railway Link	Status
1.	DKI Jakarta-Bogor	developed
2.	DKI Jakarta-Bekasi-Karawang-Cikampek	developed
3.	Cikampek-Purwakarta-Padalarang-Bandung	-
4.	Cikampek-Cirebon	-
5.	Bandung-Tasikmalaya	-
6.	Tegal-Pekalongan-Semarang	-
7.	Yogyakarta-Klaten Surakarta	-
8.	Kertosono-Jombang-Mojokerto-Surabaya	-

The equilibrium solution for Do Something A (road investment) is summarized in **Table 7**, and for rail investment in **Table 8**. **Table 7** and **8** also show the differences that may be available if the investment is implemented.

Table 7. Optimum Solutions for the Java Network – Road Investment - Do Something A

	JAVA NETWORK – ROAD INVESTMENT				
	Cost (ton.hr.)	Road Usage		Rail Usage	
		ton.km	%	ton.km	%
Do Nothing	1457680	9394799	39,78	14221084	60,22
Do Something	1450339	9626757	40,77	13987158	59,23
Saving	**0,50%**				

From **Table 7** can be seen that, when comparing optimum results of do nothing and do something A, the road investment scenario achieves a better solution. The do something A results in a 0.99% rail mode usage, in terms of ton-km, diverting to road. This yields a different of 0.50% of the total transport cost relative to the base condition. **Figure 7** show flow pattern for Java island network in do something A scenario.

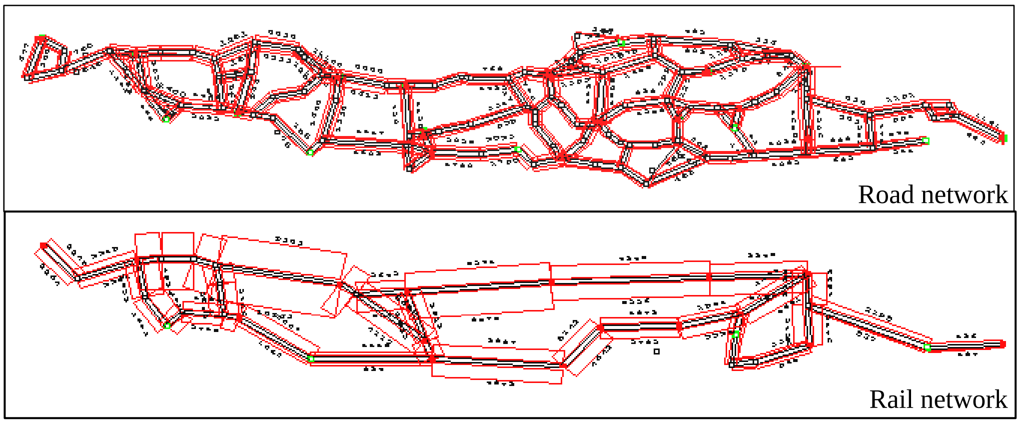

Figure 7. Flow Pattern (Do Something A)

Table 8. Optimum Solutions for the Java Network – Railroad Investment - Do Something B

	JAVA NETWORK – RAILWAYS INVESTMENT				
	Cost (ton.hr.)	**Road Usage**		**Rail Usage**	
		ton.km	**%**	**ton.km**	**%**
Do Nothing	1457680	9394799	39,78	14221084	60,22
Do Something	1353995	8666990	36,56	15036316	63,44
Saving	**7,11%**				

From **Table 8** can be seen that, when comparing optimum results of do nothing and do something B, the railroad investment scenario achieves a better solution. The do something B results in a 3.22% road mode usage, in terms of ton-km, diverting to rail. This yields a different of 7.11% of the total transport cost relative to the base condition. **Figure 8** show flow pattern for Java network in do something B scenario.

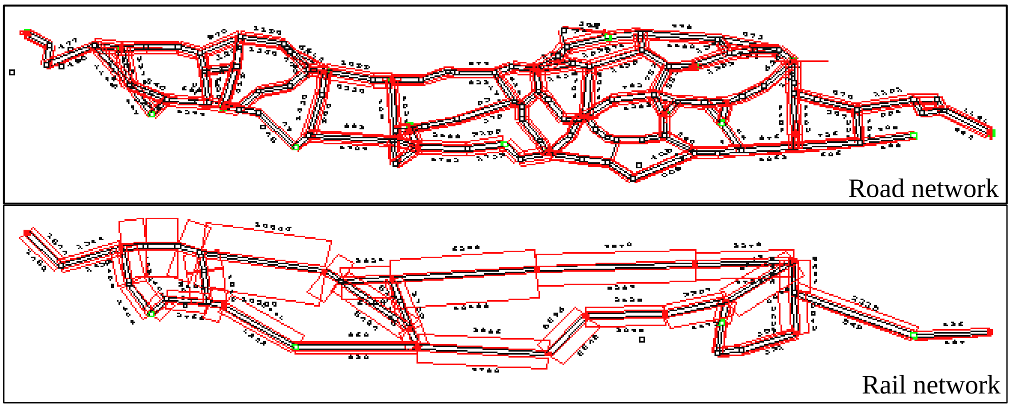

Figure 8. Flow Pattern (Do Something B)

In the do something scenario, the railroad investment scenario has a higher saving than the road investment scenario.

5. CONCLUSION

From implementation's result on artificial network was tested above can summarized that there are inefficient on the network, which can got from UE condition relative to SO condition, in term of system cost total (veh.sec/hour). Level of inefficient for the artificial network is 8.69%.

On freight transport network in Java Island, for base condition case, there are inefficient of mode usage. It can be seen that the SO routing results in a 5.19% of road mode usage, in terms of ton-km, diverting to rail. The SO condition yields a benefit of 2% of the total transport cost relative to the base UE condition. In the do something A condition, there are 0.99% rail mode usage, in term of ton-km, diverting to road. This yields a different of 0.50% of the total transport cost relative to the base condition. And in the do something B condition, there are 3.22% road mode usage, in term of ton-km, diverting to rail. This yields a different of 7.11% of the total transport cost relative to the base condition.

Based on result of implementation above, it can achieved a conclusion that equilibrium approach only reproduce assign traffic flow optimally from user side. But it can’t represent optimal condition in context of network system. So, in the road network system models need to done evaluation using SO method that can achieve the better solution. Practically, implementation of SO method can be applied on traffic management scheme, i.e.: road pricing, link directional, parking policy, etc.

REFERENCES

Beckmann, M., McGuire, C. and Winsten, C. (1956) **Studies in the Economics of Transportation**. Yale University Press, New Haven.

Directorate of Urban Road Development (1997) **Indonesian Highway Capacity Manual**. Directorate General Bina Marga, Jakarta.

Ortuzar, J.D., Willumsen, L.G. (1990) **Modelling Transport**. John Wiley&Sons, Chichester.

Prasetyo, L.B.B. (1999) **Modelling Intermodal Transfers of Freight Transportation Network**. Master Thesis, Sistem dan Teknik Jalan Raya, ITB.

Sheffi, Y. (1985) **Urban Transportation Network**. Prentice-Hall, New Jersey.

Wardrop, J.G. (1952) “Some Theoretical Aspects of Road Traffic Research”, **Proc. Inst. Civ. Eng.**, Part II, 1, pp.325-378.