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FUNCTIONAL AND ECONOMIC EVALUATIONS FOR CHOOSING ROAD INTERSECTION LAYOUT

ABSTRACT

The road intersection design requires a choice among different layouts, for example signalized intersections or roundabouts. Generally, layouts which provide higher level of services are the most expensive ones. For this reason, the choice has to consider both fixed and variable costs, the latter consisting in the delays suffered by the drivers crossing the junction. The paper presents a procedure to compare different layouts, taking into account the costs of construction, management/maintenance and delays. The cost of delay is estimated with different traffic conditions, by the evaluation of the layout performance, in terms of delays at the approaches. With the example traffic conditions and parameters values considered in the paper, the compact roundabout turns out to be the layout with the least overall cost. The examples of sensitivity analyses are also provided to understand the cost dependence on the parameters used.

KEY WORDS

roundabouts, signalized intersections, delay, traffic, cost

1. INTRODUCTION

Technical economic analyses have been proposed, recently also for roundabouts [1]. These analyses can cover different aspects, spanning from complete cost benefit analyses to simpler approaches.

Cost benefit analyses were developed from the beginning in all fields of transportation engineering, both for design and management (see e.g. [2] or [3]). Applying these methods, however, one has to deal with variables which are difficult to express in monetary values.

This happens mainly with environmental or landscape-related variables [4]: the results can hence be affected by certain arbitrariness. If only the construction costs (land and pavement costs, etc.) are compared, the functional aspects are neglected, which have direct economic impact and can be objectively evaluated.

Thus, the paper shows comparisons between different layouts, signalized intersections and roundabouts, considering construction costs along with functional performances. Further effects not easily assessable are neglected, such as social costs. However, rough analyses based only on construction costs are refined.

The aim of the paper is hence to give a methodological and operative tool for technical economic analyses which can be readily implemented. Moreover, this tool can lead to clear results, easy to understand, without the difficulties appearing in the more complete cost benefit analyses, which use variables (e.g. environmental and socioeconomic) having a monetary value hard to assign and often disputed. In detail, the topic covered by the paper is described as follows.

A road intersection can be arranged following different layouts. For instance, at-grade intersections can be signalized or non-signalized, traditional or roundabouts.

When a new junction or the renewal of an existing one is needed, the most appropriate layout has to be chosen. This choice depends not only on technical, but also on policy criteria.

With regard to the traffic theory, an intersection layout is correct if it allows an acceptable level of service during peak hours, that is, the highest expected traffic flows are not linked with excessive delays for the drivers: the shorter the delays for the traffic flows crossing the intersection, the better the layout.

Besides, also the economic constraints play a role. The best layout is hence the least expensive one, with respect to construction, operation and maintenance.

Generally, technical and economical issues are conflicting, because the most efficient layouts are usually the most expensive ones.

So it is important to compare the operational advantages (short delays) with the reduction in construction and managing costs. In order to perform this comparison, a monetary value has to be assigned to the delay, i.e. the time wasted by the drivers. So a less efficient intersection with long delays deals with higher time costs, while a more efficient one has instead higher fixed costs.

A functional and economic evaluation is hence possible for a rational choice of the intersection layout.

2. COST COMPONENTS

The overall costs of a road intersection consist of:

- fixed construction costs;
- land;
- pavement;
- traffic signal;
- variable costs;
- management and maintenance;
- time (delays).

Other costs could also be considered, such as safety costs (as explained for example in [5]) or hedonic benefits (i.e. negative costs) related to the aesthetic perception of different intersection layouts, or other costs related to any intersection effect.

For example, a comparison based on safety would need the use of potential accident rate models, either for signalized intersections or for roundabouts (such as the one developed by the authors [6]).

However, since the paper aims to show a methodological approach rather than to cover all of the possible factors influencing the comparison, only the abovementioned factors are explicitly analyzed. These allow in fact the easiest and most direct calculation. Hence, with the presented computational procedure it is possible to consider other factors, such as safety.

Land cost depends strictly on the location of the junction: it is the highest in the central urban areas and decreases with distance from the centre. In an extra-urban area the indicative values run between 50 and 100 €/m^2. The pavement cost varies with the type of material used. The cost for typical asphalt pavement (considering all the foundation layers) is about 30 €/m^2).

The traffic signal cost clearly applies only to signalized intersections: for a four-leg layout, with a two-phase preset cycle, a reference value including installation is € 40,000.

The maintenance and management costs vary with the type of intersection, i.e. signalized and non-signalized intersections and roundabouts. Signalized intersection requires electricity and maintenance and incurs annual costs of about €4,000. In the case of roundabouts costs are related to the dimension and arrangement of the central island. Here the islands with gardens are considered. The indications from municipal services give annual values from €1,000 for compact roundabouts to €10,000 for greater diameters. All the indicated values are guidelines, since every intersection has its specific features and location. They serve only as the basis of the example calculations presented in this paper. In order to compare the cost of the delay with other layout costs, the total annual delay is needed, i.e. the sum of all delays suffered by the drivers crossing the intersection during one year.

Since the traffic flow and hence the delays change with time, the annual delay is calculated using the traffic demand curve. This is a diagram indicating the annual hours in which a certain flow value is attained. Its shape is related to the road usage (see *Figure 1*): a route where traffic is high only in several periods, e.g. tourist destination, leads to a very steep initial decrease in flow volume relative to the maximum volume, whereas the curve for an urban road, where peak volumes are reached every workday, has a more steady decrease.

Annual delay D is obtained by:

$$D = \sum_j \left[d(Q_j) \cdot T(Q_j) \cdot Q_j \right] \qquad (1)$$

- Q_j [veh/h] is every traffic flow reference value;
- $d(Q_j)$ [s] is the average delay associated with a total flow Q_j;
- $T(Q_j)$ [h] is the yearly amount of hours with the registered flow equal to Q_j;

The detailed procedure is:

- starting from the peak annual flow, these values have to be divided into an adequate number of intervals, e.g. 20: from 0 to 5% Qmax, from 5% to 10%, etc.;
- the demand curve gives the number of hours per year in which the traffic demand lies in each interval;
- assuming the mean values of each class, literature methods (e.g. HCM for at-grade intersections and AustRoads for roundabouts) lead to mean delay for the different movements and hence for the entire intersection;
- the annual delay is finally obtained by eq. (1).

Table 1 reports an example of the described calculation.

Once the annual delay is known, its value has to be multiplied by the unit cost of time to give the annual cost associated with the delay caused by the intersection.

This time cost can be chosen to include also fuel and environmental costs, assuming these costs are proportional to delays. Then the overall cost can be calculated, taking into account the whole infrastructure life. Costs relative to years following the construc-

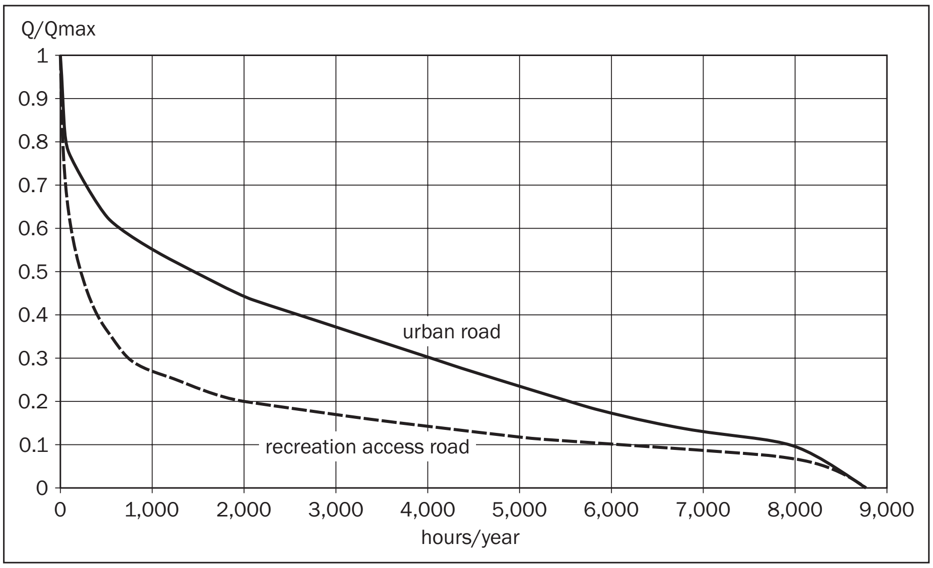

Figure 1 - Traffic demand curves

tion (management and delay) have to be converted to present values, considering a discount rate i.

$$C_{tot,0} = C_{fix,0} + \sum_{n=1}^{T} \frac{C_{var,n}}{(1+i)^n} \quad (2)$$

3. TECHNICAL AND ECONOMIC ANALYSIS: COMPARISON OF DIFFERENT LAYOUTS

Here the total costs (construction, management and delay) of six intersection layouts are analyzed.

Table 1 - Example calculation of the annual delay, according to two different traffic demand curves (compact roundabout, q_{max} = 2,400 veh/h)

Qj / Qmax (interval)	Qj / Qmax (mean value)	Qj [veh/h]	Average delay [s/veh]	Recreation access road demand curve [h/year]	Urban road demand curve [h/year]	Annual delay (recreation access traffic) [s/year]	Annual delay (urban traffic) [s/year]
0.95 - 1	0.975	2,340	50.6	5	7	592,180	829,052
0.90 - 0.95	0.925	2,220	29.8	5	10	330,890	661,780
0.85 - 0.90	0.875	2,100	24.4	5	16	256,665	821,328
0.80 - 0.85	0.825	1,980	21.8	5	34	215,768	1,467,220
0.75 - 0.80	0.775	1,860	20.3	15	83	565,402	3,128,558
0.70 - 0.75	0.725	1,740	19.2	18	130	600,849	4,339,468
0.65 - 0.70	0.675	1,620	18.4	27	145	803,101	4,312,948
0.60 - 0.65	0.625	1,500	17.9	37	225	992,714	6,036,776
0.55 - 0.60	0.575	1,380	17.4	50	350	1,199,069	8,393,481
0.50 - 0.55	0.525	1,260	17.0	58	467	1,239,335	9,978,787
0.45 - 0.50	0.475	1,140	16.6	75	467	1,419,777	8,840,475
0.40 - 0.45	0.425	1,020	16.3	100	667	1,662,884	11,091,435
0.35 - 0.40	0.375	900	16.0	150	700	2,165,279	10,104,637
0.30 - 0.35	0.325	780	15.8	200	700	2,465,812	8,630,342
0.25 - 0.30	0.275	660	15.6	500	778	5,147,652	8,009,746
0.20 - 0.25	0.225	540	15.4	750	778	6,241,828	6,474,856
0.15 - 0.20	0.175	420	15.2	1,800	944	11,522,866	6,043,103
0.10 - 0.15	0.125	300	15.1	2,200	1,300	9,956,804	5,883,566
0.05 - 0.10	0.075	180	14.9	2,190	551	5,890,230	1,481,971
0 - 0.05	0.025	60	14.8	570	408	506,454	362,514
Total annual delay:						53,775,558	106,892,044

Three of them are four-leg signalized intersections, and three are four-leg roundabouts.

Four-leg signalized intersection:

- single lane approaches;
- double lane approaches on the major road, single lane on the minor;
- double lane approaches;

Four-leg roundabout:

- compact single lane roundabout: external diameter 30m, single lane approaches and single lane circulatory roadway;
- large double lane roundabout: external diameter 80m, single lane approaches and double lane circulatory roadway;
- large double lane roundabout: external diameter 80m, double lane approaches and double lane circulatory roadway.

These layouts were chosen to represent both traditional intersections and roundabouts, and for each scheme a lower and an upper dimensional limit, along with an intermediate case. The analysis can hence show the trend in all cost components, by varying the intersection size.

The six layouts were compared following the procedure described above.

The surfaces of the entire layout and of its paved area were measured considering also all approaches up to a distance of 120m from the centre of the intersection or roundabout, therefore taking into account every width variation of the merging roads.

The delays at roundabouts were calculated following the AustRoads procedure [7], whereas delays at signalized intersections were computed using the HCM method [8]. For an updated review of the criteria for the calculation of delay and capacity in the intersection see for example [9], [10] and [11].

In the first case, the entering hourly volumes lead straight to the capacity evaluation and to the average delays for the different approaches, and hence to the average delay for the whole traffic crossing the roundabout.

For signalized intersections, however, the delays can be obtained only after the definition of the signalization conditions: cycle length, phase plan, green times, etc. Therefore, a design of the signalization was performed for each traffic condition considered,. The cycle length and the green times were chosen in order to minimize the average delays at the intersection.

For both roundabouts and signalized intersections, the geometric delay, based on the real paths followed by the drivers and their speeds, was added to the functional delay obtained from the above mentioned procedures, for a complete evaluation of the layout performance.

The traffic conditions used for the evaluations are those of a major road which crosses a minor road having half the traffic volume. The flows are equally divided into the two directions of both roads. The turning shares are 60-70% for crossing flows and 15-20% both for left and right turning flows.

The maximum traffic volume for the entire intersection was set at 2,400 veh/h, to give the entering flows of 800 veh/h on each approach of the major road and 400 veh/h on the minor road approaches.

The land and pavement cost were set at 100 and 30 €/m^2, the delay cost was set at 10 €/h, and the discount rate is 5%. *Table 2* summarizes the different cost components, while *Figure 2* shows the overall costs, calculated over 10 years. The costs related to urban roads (see *Figure 1*) are always greater than those of a tourist route. Since the maximum flow is fixed, the annual flow is greater, and so is the total delay and its cost. With the traffic conditions chosen for the comparison, the compact roundabout (diameter 30m) proves to be the most efficient layout, having both low construction costs and short delays. The two roundabout

Table 2 – Cost components (€) for the six compared layouts

Layout	Land	Pavement	Signal	Management (annual)	Delay (annual)		Overall cost (10 years)	
					Recreation access road	Urban road	Recreation access road	Urban road
Roundabout diam. 16m (1 lane)	520,000	150,000	0	1,000	149,377	295,922	1,831,168	2,962,756
Roundabout diam. 60m (1 lane)	953,300	194,250	0	10,000	191,405	356,797	2,702,749	3,979,862
Roundabout diam. 60m (2 lane)	1,121,700	243,750	0	10,000	190,472	352,870	2,913,441	4,167,434
Intersection 4x1	510,000	153,000	40,000	4,000	209,768	699,000	2,353,661	3,954,629
Intersection 2x2 2x1	568,000	170,400	40,000	4,000	192,279	774,400	2,294,018	3,720,357
Intersection 4x2	630,000	189,000	40,000	4,000	186,353	855,000	2,328,854	3,675,859

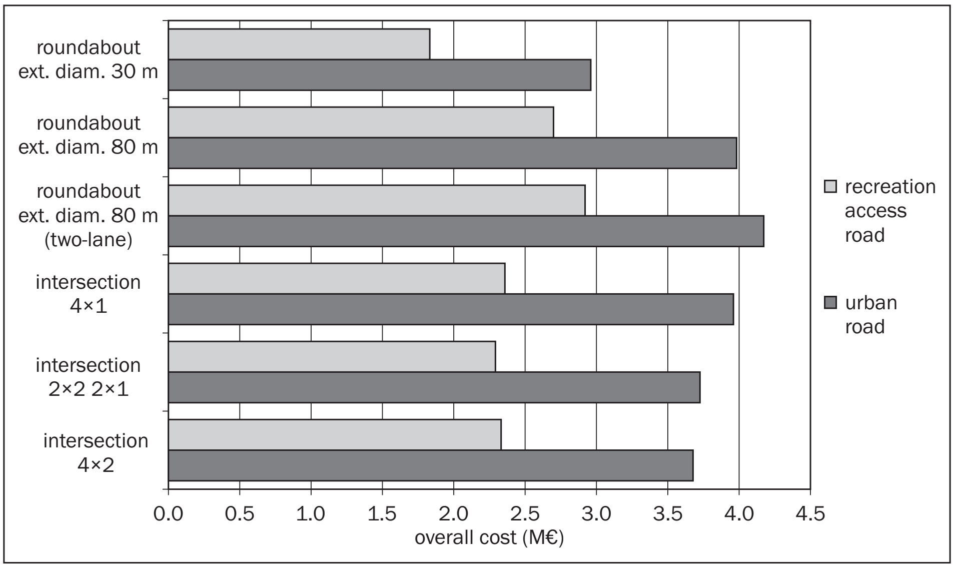

Figure 2 - Overall cost (over 10 years) for the six compared layouts

layouts having a 80m diameter (with single and double lane circulatory roadway) are much more expensive, even though they produce shorter delays with the highest annual volumes. In fact, with volumes significantly lower than the annual peak, which are the most common, the smaller roundabout takes the advantage of the shorter turning paths, leading to shorter delays.

The three signalized layouts have similar performances for tourist traffic (see *Figure 1*); however, with urban road demand, i.e. with higher flows lasting a greater number of hours per year, a layout with separate lanes for left turns performs so much better than the single lane layouts that the higher construction costs of its wider approaches are more than compensated for.

4. SENSITIVITY ANALYSIS

In order to perform the previous comparison many parameters were fixed: maximum annual traffic volume, demand curve, delay cost, discount rate. In practice, however, these data are not always known. Even when the values are correctly estimated at the present time, they can vary significantly during the lifetime of the infrastructure. This can lead to errors in the identification of the most economical layout. An example is the maximum traffic volume higher than the expected value. If the layout cannot cope with that increase, the delay will grow dramatically, and the total cost can exceed the cost of other more efficient layouts. It is hence appropriate to perform sensitivity analyses on

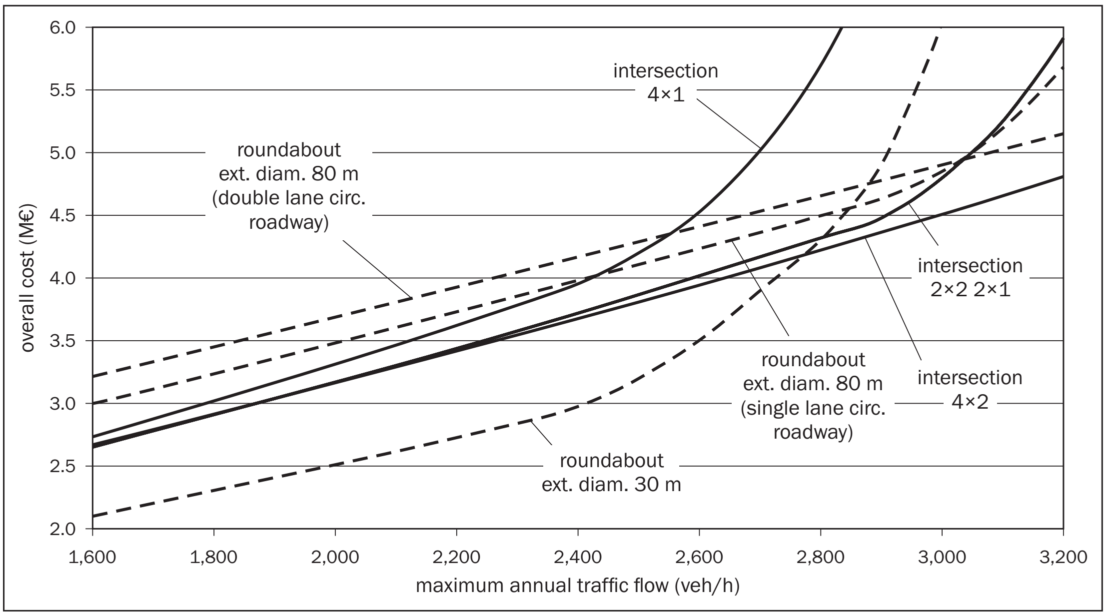

Figure 3 - Overall layout cost, function of maximum annual traffic flow (urban traffic demand curve)

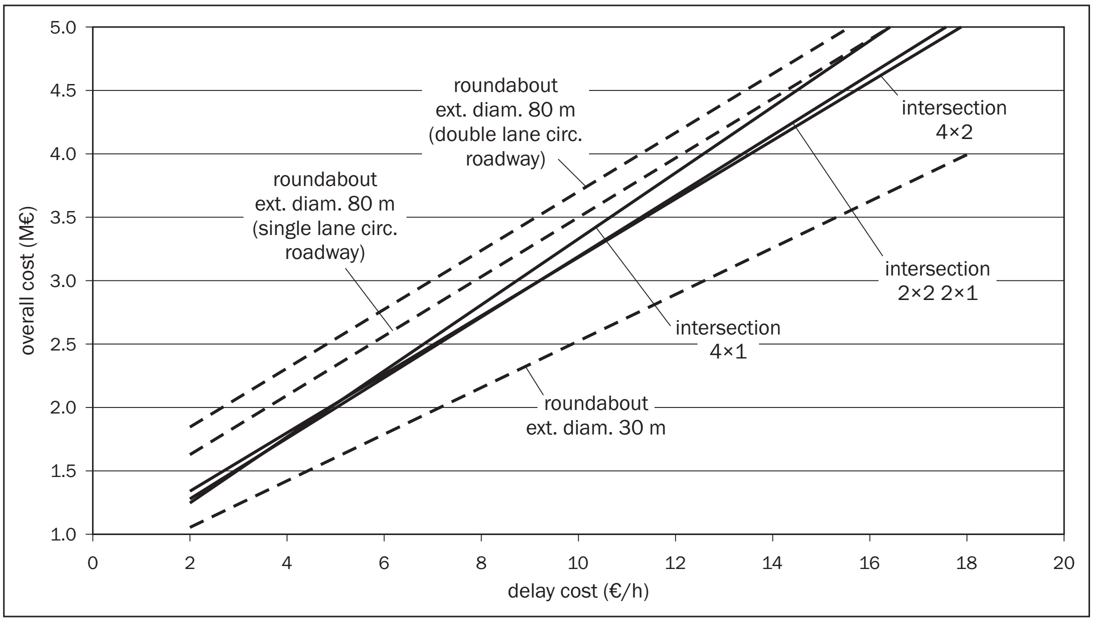

Figure 4 - Overall layout cost, function of maximum annual traffic flow and traffic demand curve

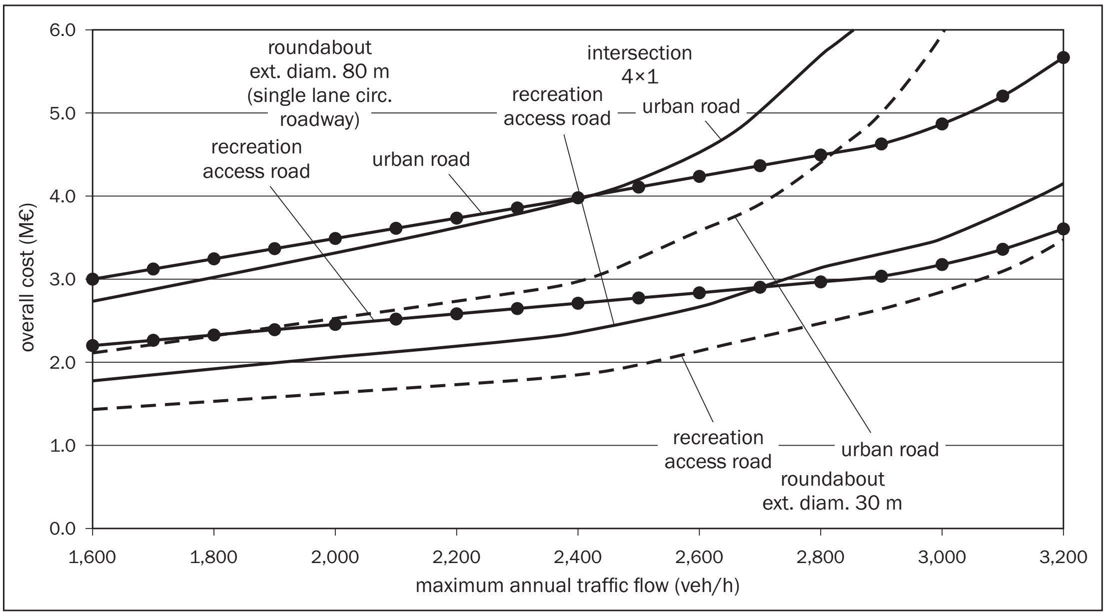

Figure 5 - Overall layout cost, function of the monetary value assumed for delay

the results. The goal is to understand the parameters effect on the overall cost, which is to be minimized. In this case, the most effective parameter is the maximum annual traffic volume. It determines if a layout is more or less efficient, with respect to the heaviest traffic peak affecting it. The following four diagrams show the overall cost for each layout, calculated following the procedure previously shown, always considering 10-year lifetime. Each diagram shows the effect of one parameter, varying in the range indicated on the horizontal axis: the maximum annual volume (*Figure 3*), the demand curve, together with the maximum volume (*Figure 4*), the delay cost (*Figure 5*), and the discount rate (*Figure 6*). With respect to the *Figure 3* diagrams, the following can be pointed out:

- the compact roundabout (external diameter 30m) appears to be the best layout for traffic volumes up to 2,800 veh/h;
- over this threshold, this layout, and also the single lane signalized intersection, proves to be inefficient, with a large increase in the delay costs;
- for maximum volumes greater than 2,800 - 3,000 veh/h, the most expensive layouts in terms of construction costs and the most efficient in terms of delays (double lane intersections and roundabouts) prove to be the better choice.

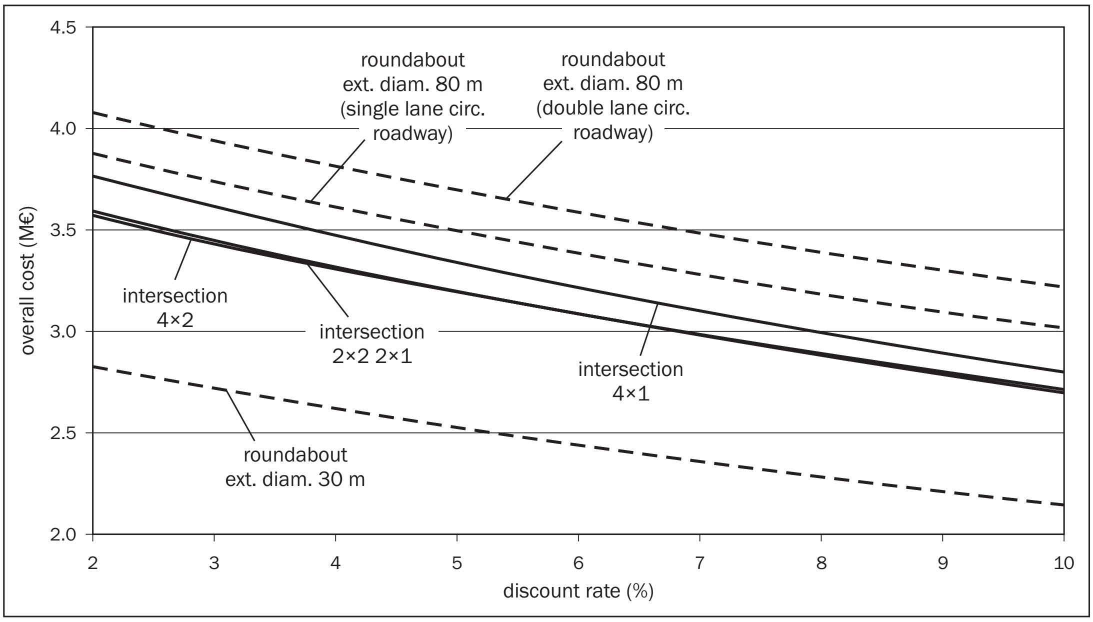

Figure 6 - Overall layout cost, function of the discount rate

5. CONCLUSION

An example of technical and economic evaluation applied to the choice of a road intersection layout (signalled intersection and roundabout) has been presented.

The analyses of this paper, however, are general and can also apply to *newly designed intersections* [12]. Overall costs have considered the delay caused by the intersection, with a monetary value assigned to it. The following parameters determine the most economic layout: construction costs, depending on the land needed for the layout and the possible systems (signal); management costs, delay costs.

Delay costs depend further on the traffic demand pattern, the maximum annual volume, the monetary value assigned to the delay, the discount rate chosen to evaluate the costs in the years after the construction.

To compare different layouts a scenario has to be defined, setting all parameters. With the example typical traffic conditions considered, the compact roundabout turns out to be the layout having the lowest overall cost: low land costs are coupled with low delays provided by the efficiency of roundabouts.

However, the parameters definition implies some uncertainties. The sensitivity analyses are hence appropriate to check the results with conditions other than expected. In practice, every single parameter was changed on a defined range, providing more detailed information, with respect to the initial assumptions. The sensitivity analyses have shown, for example, that beyond a certain threshold in the maximum flow, large intersections become the ones with the lowest costs, since the smaller ones suffer for overcapacity periods.

A firmer choice is hence possible, since the results are known, even though the conditions will be different than expected.

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ASTRATTO

CONSIDERAZIONI DI TIPO PRESTAZIONALE ED ECONOMICO PER LA SCELTA DEGLI INCROCI STRADALI

Nell'articolo si presentano i risultati di una analisi comparativa del tipo Costi-Benefici per confrontare le prestazioni di incroci semaforizzati e rotatorie ed ottenere così ulteriori elementi per la scelta del tipo di incrocio da adottare in fase di progetto o di riqualificazione di un nodo stradale.

I costi generalizzati considerati nelle analisi tengono conto degli oneri sopportati dagli utenti per le attese all'intersezione, e di quelli relativi alla costruzione, ai dispositivi di controllo ed alla gestione e manutenzione.

Questi costi sono espressi in funzione della domanda annuale di traffico che interessa l'incrocio, del valore del tempo e della vita utile di quest'ultima. Poiché la determinazione di questi parametri è affetta da incertezza, viene effettuata anche una analisi di sensitività che fornisce ulteriori informazioni nella scelta dello schema di intersezione da adottare. La procedura comparativa così messa a punto ed esplicitata e di tipo del tutto generale e può facilmente applicarsi per casi concreti, risultando di evidente utilità nella pratica tecnica

PAROLE CHIAVE

rotatoria, incrocio semaforizzato, ritardo, traffico, costo

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