How should we prioritise incident management deployment?

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1 Introduction

Transport agencies around the world are shifting focus from conventional road engineering construction to traffic management and enhancing the existing road network. Incident management deployment is part of an overall suite of non-infrastructure based deployment transport options called Intelligent Transport Systems (ITS). The objective of incident management is to minimise the safety, reliability and environmental impacts of incidents on the operations of the transport system. This may be achieved by informing travellers of the incident so they can adapt their behaviour in a manner that reduces individual and community impacts, such as lateness and the associated vehicle emissions, unreliability of travel times, as well as secondary accidents due to incidents.

The aim of evaluating ITS is four fold (Turner, Stockton et al. 1998). Firstly, ITS is evaluated to understand the social, economic and environmental impacts on the transportation system and its users. By understanding the impacts, the benefits can be quantified. Both of these elements help transport agencies to optimise public sector investments by making future investment decisions. Finally, ITS evaluations help to identify areas of improvement for existing operations or systems. With perpetual strains on resources and traffic increasing at a steady rate, transport agencies need to evaluate the road network and make informed decisions to determine which roads have the greatest risk of adverse incident impacts and therefore identify the roads that have the greatest case for intervention. This is the case for ITS and incident management, but what is the optimal evaluation method?

As with conventional transportation infrastructure projects, the most common way to evaluate ITS is using economic analyses, such as benefit-cost. Unfortunately, ITS impacts are difficult to monetise for a number of reasons. Historical information for ITS impacts is not always readily available and impacts are not transferable. In contrast to conventional projects, ITS impacts are incremental to the individual user, but usually have a much wider area of impact. Incremental changes to each individual user and project take-up-rate depend on behavioural responses. To overcome these issues, ITS impacts are usually determined using stated preference surveys and modelling tools. Moreover, the costs to quantify the impacts of ITS projects have the potential to exceed the benefits of the project outcomes.

To overcome the problems with monetising ITS impacts, agencies are increasingly applying multi-criteria analyses to evaluate ITS. The approach involves the decision-maker(s) to score and weight each criterion. A benefit cost ratio can be included as a criterion thereby combining both quantitative with qualitative criteria. There are two fundamental shortfalls of multi-criteria analyses (Tsamboulas, Yiotis et al. 1999). There is no single solution optimising all criteria, so the decision-maker must compromise between solutions. As such, the method is not well structured mathematically. Also, optimising one criterion often reduces the value of another criterion; therefore many solutions cannot be compared in terms of dominance.

The two common evaluation tools are insufficient for ITS evaluation. Therefore, a new network evaluation framework is presented in this paper for ITS and in particular incident management deployment. The framework aims to analyse the road network and prioritise roads with respect to two factors: the historical risk associated with incidents; and the cost effectiveness of implementation. To assess the historical risk, the framework initially converts social, economic and environmental impacts to a common monetary base, enabling the addition of the incident impacts. The economic impact values must be treated as relative values of measurement, not absolute costs. The second part of the framework assesses the historical risk, taking into account both the consequence of an event, measured in economic terms described above, and the probability of an event occurring based on historical information. The third uses a cost-effective ratio comparing the reduced impacts with the project costs.

The economic risk analysis presented below integrates safety, reliability and environmental impacts, providing an integrated decision-making tool for proactive ITS deployment decision-making.

2 Theoretical basis of economic risk model

The Australian Risk Management Standard defines risk as the product of the likelihood of an event and the consequence of the event as expressed in Equation 2.1 (Standards Australia and Standards New Zealand 2004).

$$R = \overline{C}P \qquad \textit{Equation 2.1}$$

Where R = the risk of an event occurring during a specified period

$\overline{C}$ = the average consequence of an event

P = the probability of an average impact event occurring during a specified period

Conventional engineering risk analysis has focused on equipment failure such as bridge and pavement failures. In this case, the risk is of an incident event impacting upon a traffic network. Therefore, an "impact event" may be defined as any incident that reduces the ability of a section of infrastructure to offer a safe and reliable means of travel. An "average" impact refers to that of a typical incident on a road segment.

Applying this general risk theory to incident management deployment is summarised in the flowchart in Figure 1 below.

To determine the annual consequences for a road segment, three types of impacts must be taken into account: safety; reliability; and environmental impacts (See Table 1).

Table 1: Consequence impact categories for incident management

Impact category	Description	Examples
Safety (S)	Impact event leading to secondary accidents	Nose-to-tail accidents due to congestion Vehicles swept while crossing flooded roads
Reliability (R)	Impact event causing drivers' excessive lateness leading to diminished user confidence	Travel time impacts from incident congestion Road flooded causing road closure
Environmental (G)	Impact event causing environmental impacts	Idling vehicles caught in congestion cause additional vehicle emissions Local air quality may impact health and greenhouse gases may impact global warming

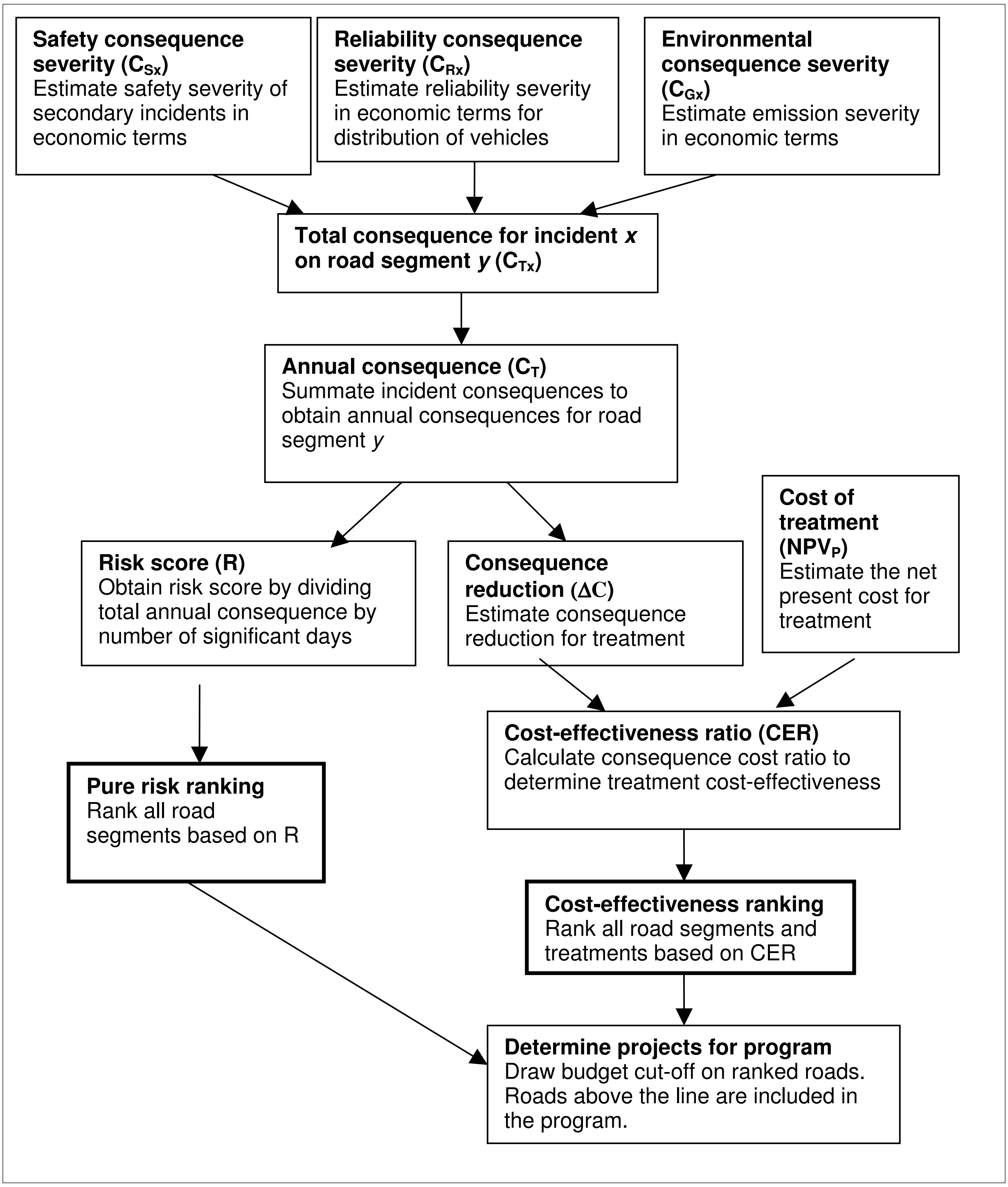

Figure 1: Economic risk analysis for road segment *y*

Annual incident consequences are determined by summating the consequence types for each incident then summating the total incident consequences for the year. Equation 2.2 below demonstrates this.

$$C_T = \sum_{x=1}^{n} (C_{Sx} + C_{Rx} + C_{Gx}) \qquad \textit{Equation 2.2}$$

Where C_T = total annual cost of consequence for road segment *y* in dollars
C_{Sx} = cost of secondary accidents for incident *x* in dollars (discussed in Section 3.1)
C_{Rx} = cost of lateness for incident *x* in dollars (discussed in Section 3.2)
C_{Gx} = cost of environmental consequences for incident *x* in dollars (discussed in Section 3.3)

n = number of incidents along road segment *y* during that time history (year)

Furthermore, the average consequences can be considered as:

$$\overline{C_T} = \frac{C_T}{n} \qquad \text{Equation 2.3}$$

Where $\overline{C_T}$ = the average incident consequence for road segment *y* described in section 3
n = number of incidents along road segment *y* during that time history (year)

The probability or likelihood of an impact event occurring is equal to the number of times an event occurs, divided by the total sample size, for example, the total number of significant days in a year (Smith 1998).

$$P = \frac{n}{N} \qquad \text{Equation 2.4}$$

Where *P* = the probability of an event occurring during a specified period
n = number of events
N = total sample size

Therefore, from Equations 2.1, 2.3 and 2.4, risk can be expressed as:

$$R = \frac{C_T}{N} \qquad \text{Equation 2.5}$$

Where *R* = risk score for road segment *y*
C_T = total annual consequence for road segment *y* described in section 3
N = number of significant days in a year depending on road type shown in Table 2

Table 2: Number of significant days for each road type

Road type	Number of significant days in a year (N)
Urban arterial	250
Urban freeway	250
Rural	365

Using the risk score shown in Equation 2.5, the pure risk of each road segment can be used to rank roads from the highest risk, to the lowest risk. This provides the decision-maker with important information regarding roads with the highest incident impacts on users.

ARRB have developed a road safety risk management methodology and software for Austroads. The work provides a decision making tool to evaluate the benefits associated with a wide range of road safety engineering treatments. The tool takes account of the road safety risk before a treatment, as measured by exposure likelihood and severity outcomes of road crashes and provides research data to measure the reduction in risk after treatment. Incorporating the treatment cost provides a Risk Reduction Cost Ratio that allows for prioritisation of different projects across the network (Austroads 2003). The idea is similar here, but to use the reduced value as a cost, the reduction is determined in terms of cost of consequences.

$$\Delta C = C_{before} - C_{after} \qquad \text{Equation 2.6}$$

Where ΔC = reduced cost of consequences for road segment *y*
C_{before} = cost of consequences before treatment
C_{after} = cost of consequences after treatment

The consequence reduction calculation is a calculation determining the impact reduction if ITS, for example Variable Message Signs (VMS), were deployed. From the consequence cost reduction, a consequence cost ratio can be calculated to ensure resources are distributed in the most cost-effective manner.

$$CER = \frac{NP\Delta C}{NPV_P} \qquad \textit{Equation 2.7}$$

Where *CER* = consequence cost ratio for road segment *y*

$NP\Delta C$ = consequence cost reduction in present value terms for road segment *y*

NPV_P = net present cost of treatment for road segment *y*

Ranking the roads from highest consequence cost ratio to the lowest enables a systematic and justifiable method of prioritising incident management deployment. This is the second type of ranking: cost-effective consequence reduction. Both methods of ranking are necessary for both minimising the incident network impacts on the community and maximising resource effectiveness.

3 Monetising incident impacts

The consequence of a traffic incident can be considered as the collective severity of an event on the individuals exposed to the event. This may be broken into two parts as shown in Equation 2.8 below. Firstly, the number of individuals exposed over the duration of the impact event; and secondly, the severity of the impact event upon each individual exposed to it. The severity or impact of an event can be expressed in economic terms.

$$C_i = E_i I_i \qquad \textit{Equation 2.8}$$

Where C_i = consequence of impact event *i*

E_i = number of individuals exposed to impact event *i*

I_i = severity of impact event i with respect to each individual

Each impact event needs to be monetised from the available routine data from the road network. This is described in more detail in the following sections.

3.1 Safety impacts

The safety impacts of incidents include secondary accidents. We define a secondary accident as an accident that occurs within half an hour of the initial accident along the same road segment. The initial accident is not included in this analysis since the focus of this research is related to reducing the impacts of incidents, rather than reducing incidents in the first place. However, further work can be done on the use of incident mitigation strategies to prevent accidents.

The safety impact values in Table 3 are measured in crash costs by severity categories: fatalities; serious injuries; minor injuries; and property damage taken directly from Section 4.2 in Austroads' "Guide to Project Evaluation Part 4: Project Evaluation Data" (Austroads 2004). These values are state averages for Queensland and relate to the total community costs associated with road crashes. Austroads recommend that the values are suitable for general road project evaluation where precise definitions of crash types are not required. Property damage (PDO) is included in the analysis since this type of damage also has community impacts and can be improved by incident management services.

Table 3: Safety Impact Values (I_S), based on (Austroads 2004)

Secondary Accident Type	Non-urban $ AUD	Urban $ AUD
Fatal	1,687,600	1,584,500
Serious injury	411,600	387,700
Minor injury	17,100	16,600
PDO	6,500	6,500

Safety impacts of incidents can be expressed in terms of number of individuals exposed and severity of impact. Equation 2.9 below is derived from Equation 2.8.

$$C_{sx} = \sum_{k=1}^{4} E_{sxk} I_{sxk} \qquad \textit{Equation 2.9}$$

Where C_{sx} = cost of secondary accidents for incident *x* in dollars
E_{sxk} = expected number of individuals involved in incident x and secondary accident type *k*
I_{sxk} = safety impact (secondary accidents) values for incident *x* and secondary accident type *k* in dollars
k = incident types as shown in Table 3

3.2 Reliability impacts

The reliability impacts of incidents include travel time greater than the average expected travel time taking into account the time of day, that is, lateness. Therefore reliability is measured with respect to the unpredictable travel time for drivers and passengers in both private and commercial vehicles. The cost of lateness depends on the following exposure and severity factors: volume of traffic exposed to the incident; average occupancy of vehicles (i.e. the number of occupants of each vehicle); distribution of vehicle types; duration of the incident; lateness caused by the incident; and the percentage of road blocked to traffic. Therefore, the generic consequence equation (Equation 2.8) can be expressed for reliability impacts as Equation 2.10.

$$C_{Rx} = \sum_{j=1}^{9} DL'D'K'V_j T_j \qquad \textit{Equation 2.10}$$

Where C_{Rx} = cost of lateness for incident *x* in dollars
D = estimated lateness caused by incident *x* in hours
L' = percentage of road closure/blocked factor for incident *x*
D' = directional distribution factor of carriageway impacted upon by impact event for incident *x*
K' = proportion of AADT occurring during incident *x*
j = vehicle type
V_j = average daily volume of vehicle type *j*
T_j = average travel time value for vehicle type *j* (see Table 4) in dollars

Table 4: Reliability Impact Values (I_E)
Based on Table 3.9 (Austroads 2004)

Vehicle types	Austroads classification (j)	Average travel time value ($/person/hour) ($T_j$) Non-urban	Urban
1. Passenger cars	1, 2	22.38	22.60
2. Light and medium rigid trucks	3	25.33	27.22
3. Heavy rigid trucks	4, 6	24.95	29.53
4. 4 axle articulated trucks	5, 7	31.12	40.99
5. 5 axle articulated trucks	8	33.92	46.51
6. 6 axle articulated trucks and rigid (3 axle) plus dog trailer (5 axle)	9	37.95	48.51
7. B-double, twin steer (4 axle) plus dog trailer (4 and 5 axle)	10	41.48	39.91
8. Double road train, B triple combination, A B combination and double B-double combination	11	54.54	-
9. Triple road train	12	62.62	-

Austroads (2004) have developed values of travel time for vehicle types based on surveys and occupancy values for each vehicle type. This information has been averaged and adopted to suit the count data collected (see Table 4). However, since there is a considerable difference between the private and business passenger car values in the original Austroads table and the trip purpose cannot be measured by traffic count analyses, the values in Table 4 are based on the split of business and private trips from the 2004 South East Queensland (SEQ) Travel Survey. Table 5 below indicates the values used.

Table 5: Proportion of total passenger car trips by purpose

Passenger car trip purpose	Proportion of total trips (%)
Business (work-based)	29.5
Private (home-based)	70.5

Most project evaluation methodologies recommend the use of a single value of time for all levels of delay or lateness. In addition, we have tested the impact on the results of adopting a different approach where short delay (up to 20 minutes) are valued differently from longer delays (over 1 hour), as shown in Figure 2. The evaluation guidelines developed by the UK Department of Transport has valued unexpected delays or lateness at up to five times in-vehicle time (UK Department of Transport 2005).

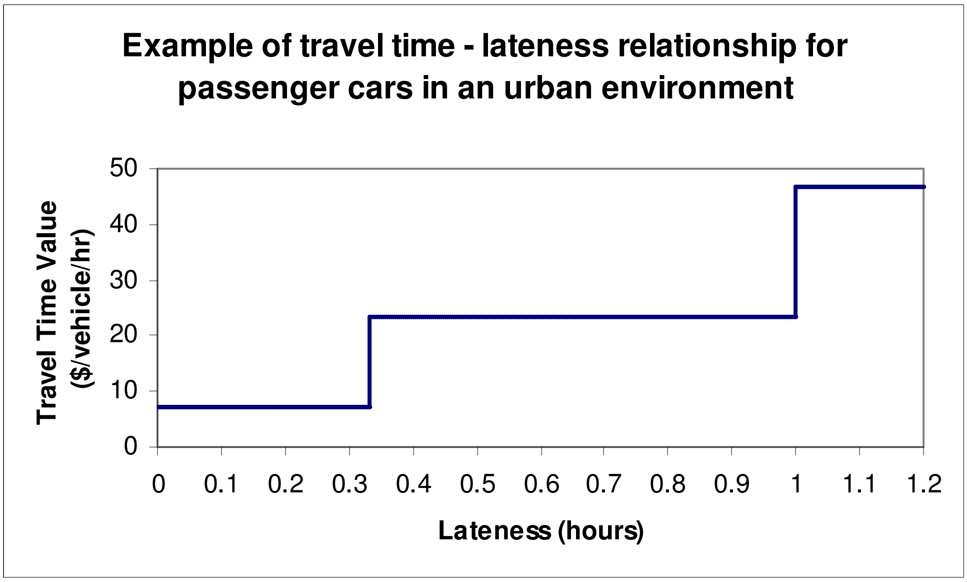

Figure 2: Example of relationship between lateness and travel time

The percentage of road closed or blocked is represented by L'. This factor represents reduced capacity caused by the incident. Table 6 are the values used in this analysis.

Table 6: Percentage of road closed/blocked factor (L' factor)
Based on Table A-10 in Stockton, Walton et al. (2003)

Number of lanes in each direction	Shoulder disablement	Shoulder accident	Lanes blocked		
			One	Two	Three
2	0.05	0.19	0.65	1	-
3	0.01	0.17	0.51	0.83	-
4	0.01	0.15	0.42	0.75	0.87
5	0.01	0.13	0.35	0.6	0.8
6	0.01	0.11	0.29	0.5	0.75
7	0.01	0.09	0.25	0.43	0.64
8	0.01	0.07	0.22	0.37	0.59

Average daily volume data (V_j) is obtained directly from traffic count data. These volumes, by vehicle type, must be converted into the volume of vehicles exposed to the incident. This is achieved through the K' and D' factors. K' is the proportion of the daily volume occurring during the incident. D' is the directional distribution factor and represents the proportion of vehicles travelling in the direction affected by the incident. Equations 2.11 and 2.12 below demonstrate how K' and D' are calculated respectively.

$$K' = \frac{(V_1 + V_2)d}{AADT} \qquad \textit{Equation 2.11}$$

$$D' = \frac{V_1}{V_1 + V_2} \qquad \textit{Equation 2.12}$$

Where K' = proportion of AADT occurring during the impact event
D' = directional distribution factor of carriageway impacted upon by impact event
V_1 = hourly volume of vehicles in direction affected by incident *x*
V_2 = hourly volume of vehicles in direction not affected by incident *x*
d = duration of incident *x* (in hours)
AADT = average annual daily traffic

3.3 Environmental impacts

Tables 7 and 8 below summarise externality costs based on Tables 5.3 and 5.4 in Austroads' "Guide to Project Evaluation Part 4: Project Evaluation Data" (Austroads 2004). Valuating environmental and other externalities is relatively immature in Australia. The values shown below are based on research by environmental authorities, BTRE (Bureau of Transport and Regional Economics) and universities and require updating as research becomes available.

Noise, water pollution, urban separation and nature and landscape are environmental impacts included in Austroad's evaluation data, but are not included in this model. Vehicular noise does not increase with incident congestion. Conversely, factors such as terrain and vehicle types affect noise. Similarly, water pollution does not increase with incident congestion. Both urban separation and nature and landscape impacts are related to road construction rather than incident management.

Table 7: Environmental Impact Values (I_G) for passenger vehicles

Externality	Unit Cost (AUD$ per vehicle kilometre)	
	Urban	Rural
Air pollution	0.021	0.0002
Greenhouse / climate	0.014	0.014
Total	**0.038**	**0.0142**

Table 8: Environmental Impact Values (I_G) for freight vehicles

Externality	Unit Cost ($/'000 tonne-km)			
	Urban		Rural	
	LCV	Rigid/Artic	LCV	Rigid/Artic
Air pollution	100	22.0	1.00	0.22
Greenhouse / climate	42	4.0	42	4.0
Total	**142**	**26**	**43**	**4.22**

These impact values are determined taking into account the number of individuals affected. Therefore, the environmental consequence values can be expressed as the impact values.

$$C_{Gx} = I_{Gx} \qquad \text{Equation 2.13}$$

Where C_{Gx} = environmental consequences for incident x
I_{Gx} = environmental impact value for incident x

4 Conclusion

There is an urgent need for network analysis tools to prioritise and rank ITS and incident management services. The risk analysis framework presented in this paper forms a basis for ITS network prioritisation enabling the agency to make informed decisions. The decision-maker(s) can determine which roads require further, project-level analysis using budget information and both ranking methods: pure risk and cost-effectiveness. Using the two ranking methods is vital to ensure both community and cost-effective needs are met. The framework has been presented for consultation, and requires validation through case studies.

5 Acknowledgements

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