



Australian Government

Department of Infrastructure, Regional Development and Cities

Bureau of Infrastructure, Transport and Regional Economics

# Defining and estimating benefit–cost ratios for road maintenance

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# Outline

- Road maintenance optimisation literature
- Proposed BCR definitions
- Optimisation including estimation of BCRs
  - I. **without** budget constraints
  - II. **with present value** budget constraints
  - III. **with annual** budget constraints
- In each instance
  - method
  - case study

# Road maintenance optimisation literature

- Very large literature by civil engineers starting in 1978
  - just one article by an economist: Abelson (1975).
- Wide variety of objective functions, constraints and optimisation techniques
  - not always valid or sensible from economic viewpoint.
- Problem of combinatorial explosion: ‘np-hardness’
  - More recent articles apply genetic optimisation techniques.
- Some evidence that lessons learned from early optimisation modelling in 1980s lead to large cost savings by changing maintenance practices from costly, infrequent interventions to cheaper, more frequent preventative maintenance interventions.
  - ‘a stitch in time saves nine’.

# Current policy context

- Underspending on maintenance due to budgetary pressures is leading to high long-term costs
  - an expensive form of borrowing
  - need to better communicate the value of spending on maintenance to decision makers.

# Difficulties with defining benefit–cost ratios (BCRs) for maintenance

- Benefits and costs must come from a comparison between a with-project case and a base case.
- For maintenance treatments:
  - very large number of options to choose between
    - alternative treatment types and timings
  - arbitrariness in selecting the base case (do-minimum scenario)
  - large numbers of small projects spread across a network.

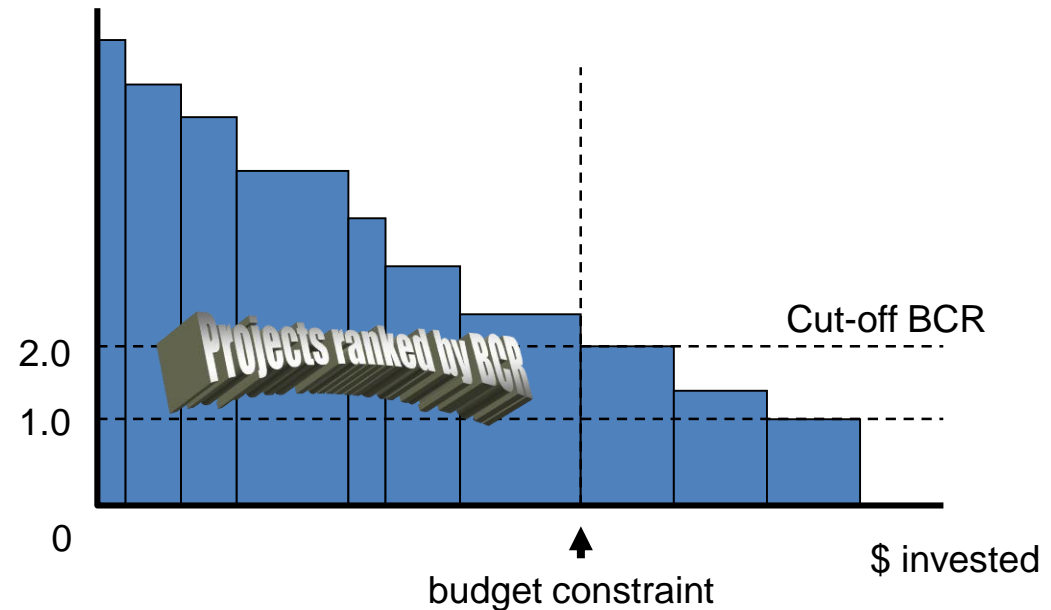
# Proposed BCR definitions

- These definitions apply to maintenance spending on a whole network, not individual maintenance projects.
- Marginal BCR (MBCR): benefit to society (expressed as a present value) of increasing the maintenance budget by an additional dollar (in present value terms).
  - instantaneous rate of change
- Incremental BCR (IBCR): same as MBCR but for a discrete increase in the maintenance budget.

# Uses of Marginal BCR for maintenance

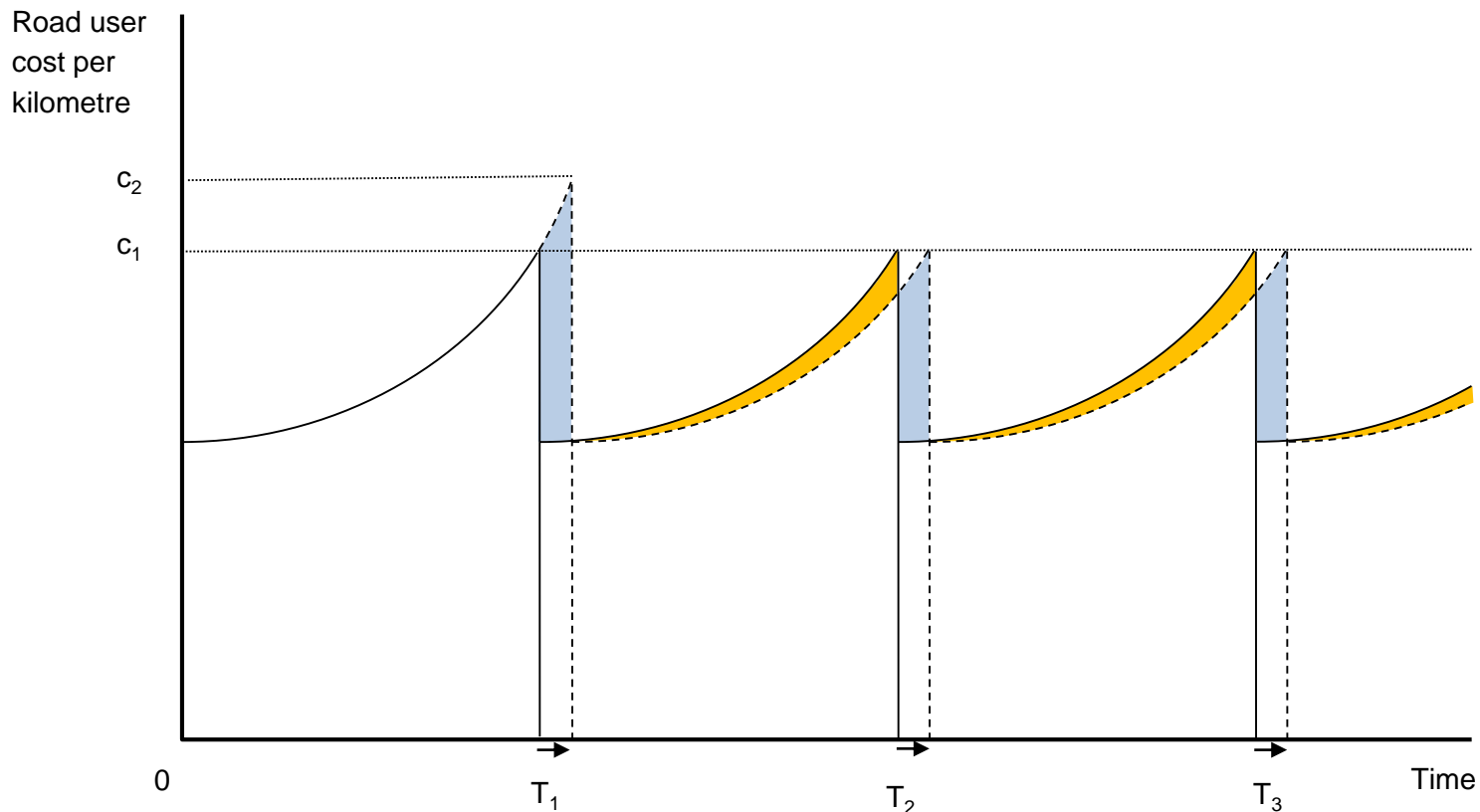
- Economic value of changing maintenance spending
- Efficient split of funds between the maintenance and capital budgets
  - comparing the MBCR for maintenance with the cut-off BCR for capital spending.

- If  $MBCR = \text{cut-off BCR}$ : optimal funds split
- If  $MBCR > \text{cut-off BCR}$ : gain from shifting funds: capital  $\Rightarrow$  maintenance
- If  $MBCR < \text{cut-off BCR}$ : gain from shifting funds: maintenance  $\Rightarrow$  capital



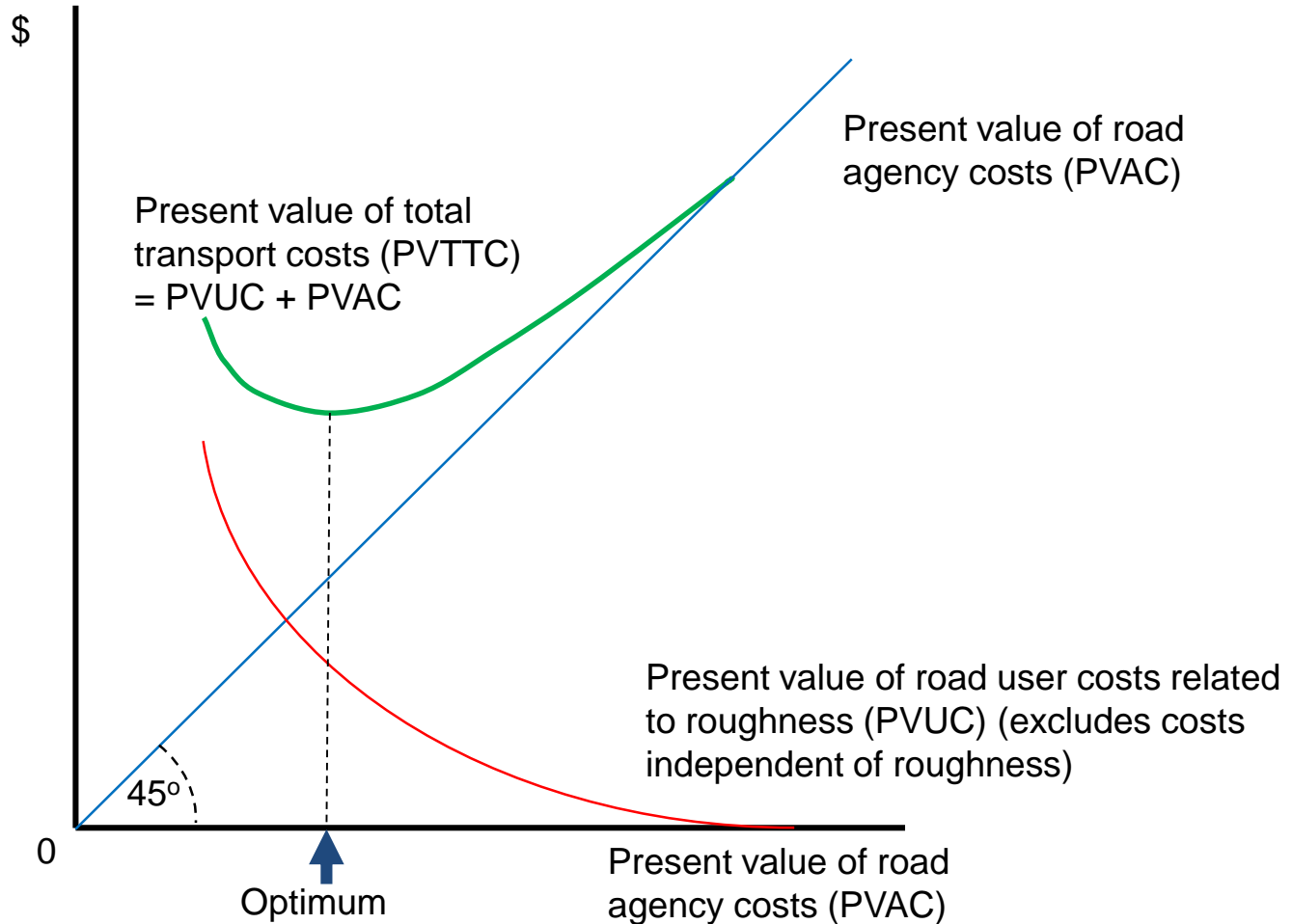
# Cost to road users from delaying a treatment

- A bitumen road roughens over time increasing user costs, until restored by a maintenance treatment.
- Delaying a treatment reduces the present value of road agency costs at the expense of a higher present value of road user costs.





# Economical optimal maintenance spending



# Marginal BCR

- The MBCR at a given value of PVAC is
  - the saving in PVUC from a one dollar increase in PVAC, which equals
  - negative the slope of the PVTTC curve plus one.

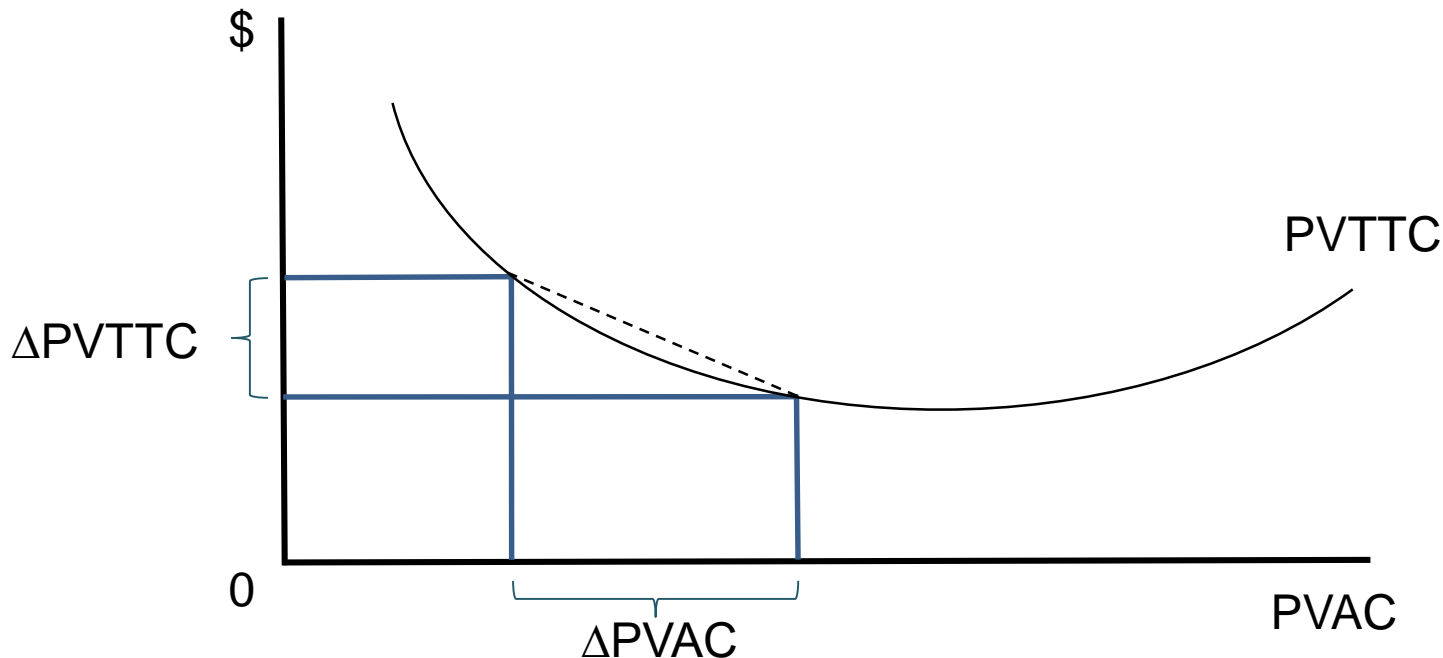
$$MBCR = -\frac{dPVUC}{dPVAC} = -\left(\frac{dPVUC + dPVAC}{dPVAC}\right) + \frac{dPVAC}{dPVAC} = -\frac{dPVTTC}{dPVA} + 1$$

MBCR = 1 at the optimum: minimum of PVTTC curve where  $\frac{dPVTTC}{dPVA} = 0$ .

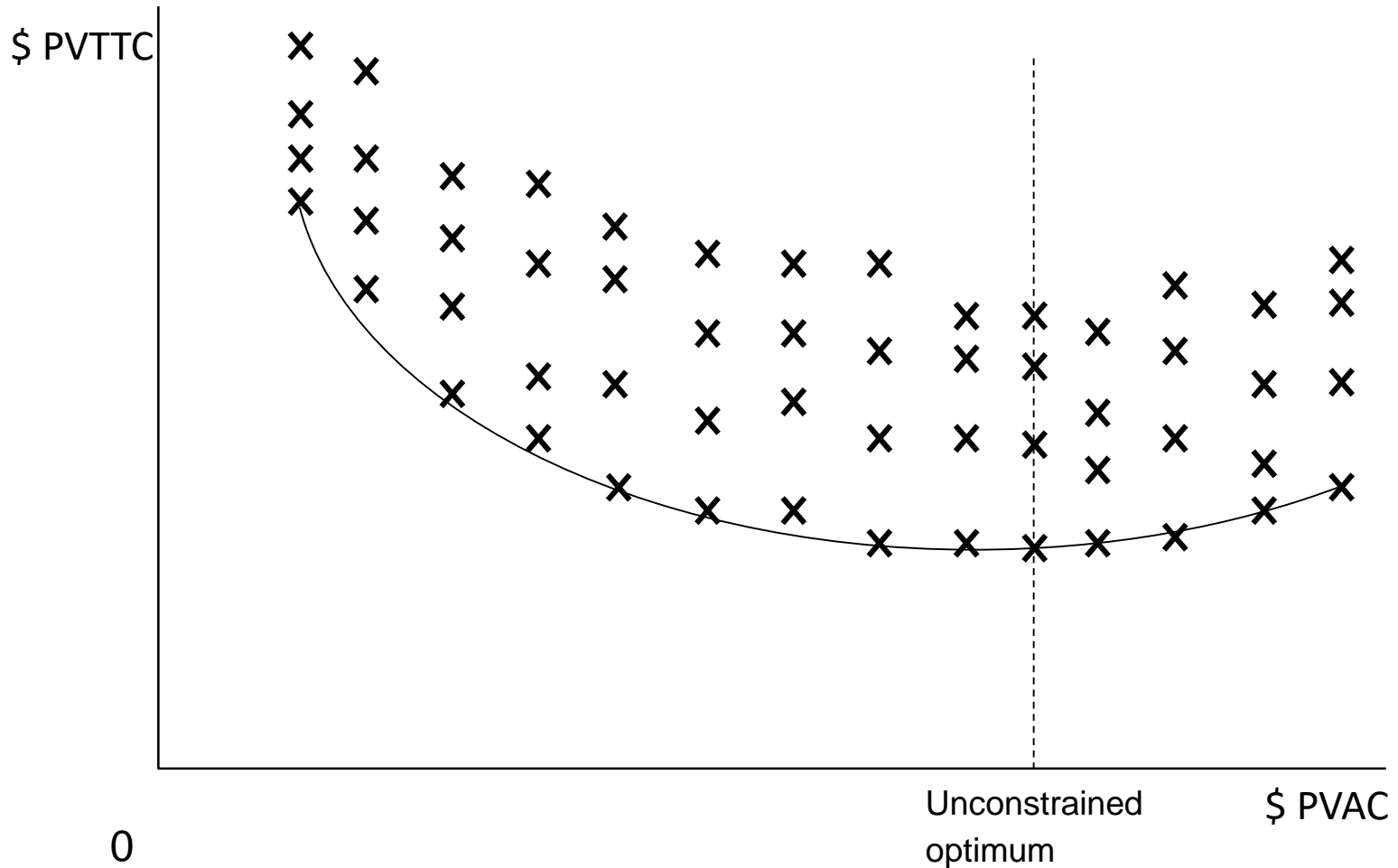
# Incremental BCR (IBCR)

- Between any two points on the PVTTC curve

$$IBCR = -\frac{\Delta PVUC}{\Delta PVAC} = -\left(\frac{\Delta PVUC + \Delta PVAC}{\Delta PVAC}\right) + \frac{\Delta PVAC}{\Delta PVAC} = -\frac{\Delta PVTTC}{\Delta PVAC} + 1$$



# Optimisation finds points on the curve



# Optimising subject to a present value budget constraint

Minimise  $PVUC(PVAC) + PVAC$  subject to  $PVAC \leq B$

$$L = PVUC(PVAC) + PVAC + \lambda(PVAC - B)$$

$$\frac{dL}{dPVAC} = \frac{dPVUC}{dPVAC} + 1 + \lambda = 0$$

Hence,  $MBCR = -\frac{dPVUC}{dPVAC} = 1 + \lambda$  at the constrained optimum.

- To optimise: for each road segment in isolation:
  - minimise  $PVUC + weight \times PVAC$ ,
    - where  $weight = 1 + \lambda = \text{target MBCR}$
  - keep doing, adjusting target MBCR until  $PVAC = \text{the constraint}$

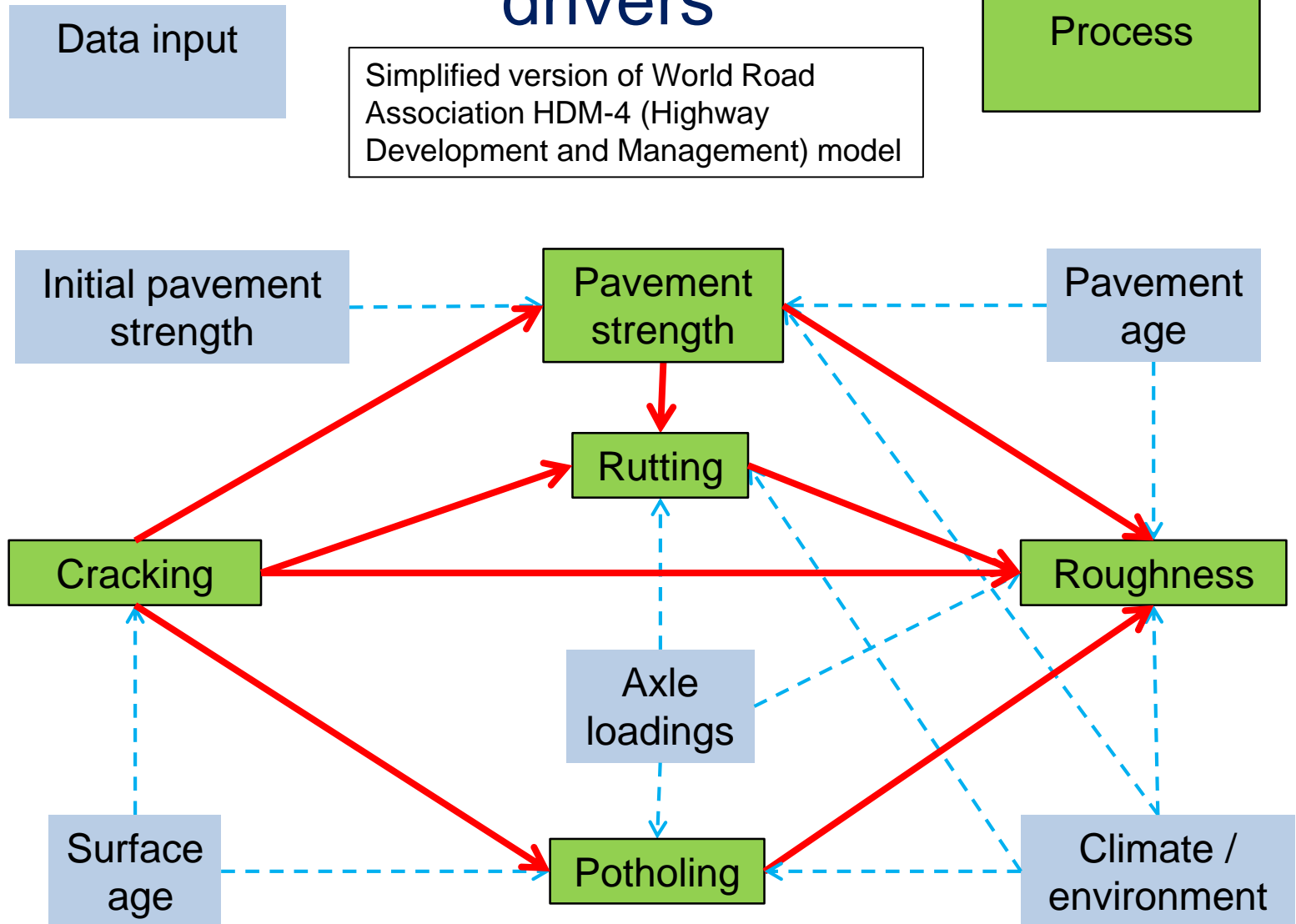
# Case study network

- Non-urban parts of the National Network in Victoria
- 1977 kilometres (92% sprayed seal, 8% asphaltic concrete)
- 2034 homogeneous road segments

# Case study: pavement model

- Periodic maintenance only
  - excludes routine maintenance except for patching potholes
- Main elements
  - deterioration algorithm
  - alternative treatments
  - road user cost relationship
  - technical constraints
  - budget constraints
  - optimisation

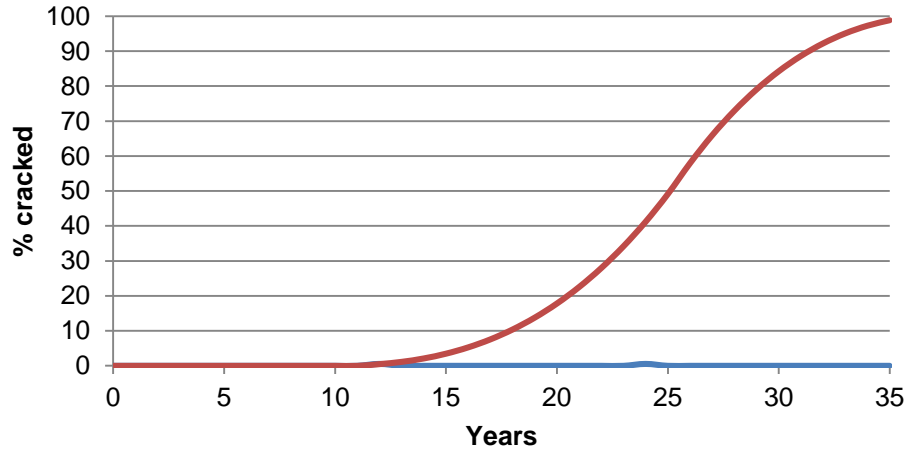
# Deterioration model: processes and main drivers



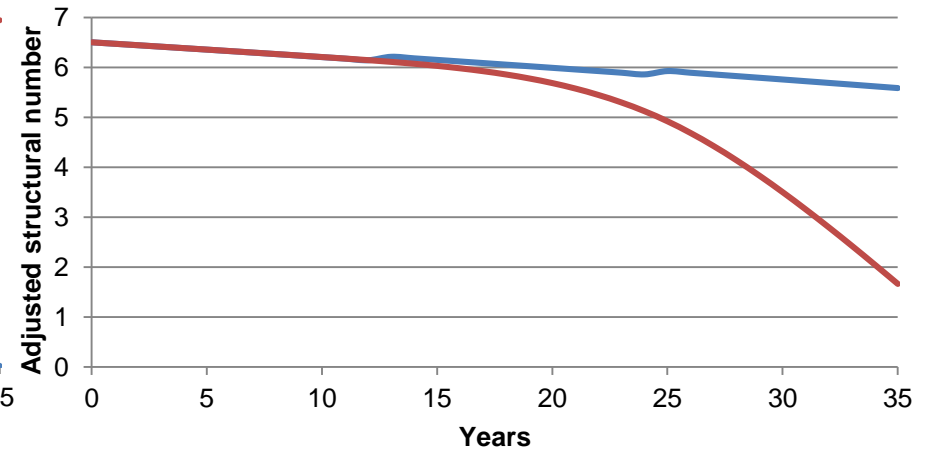


# Pavement deterioration **without** and **with** regular resurfacing: sprayed seal pavement

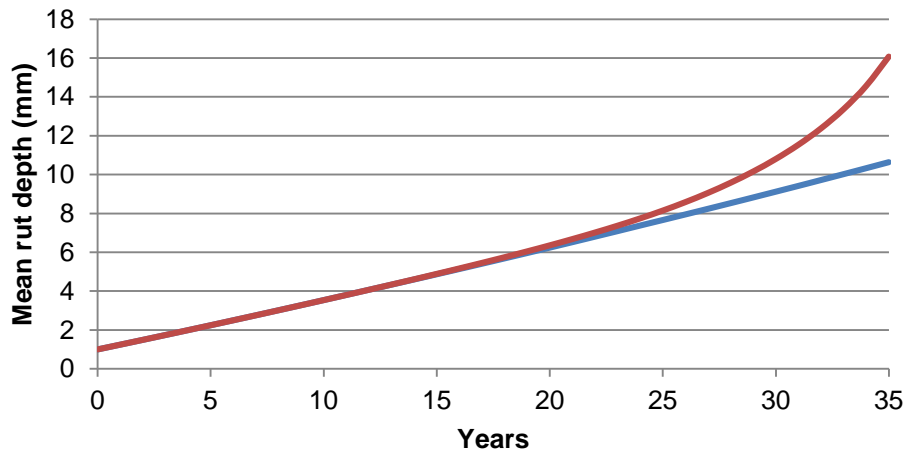
## Cracking



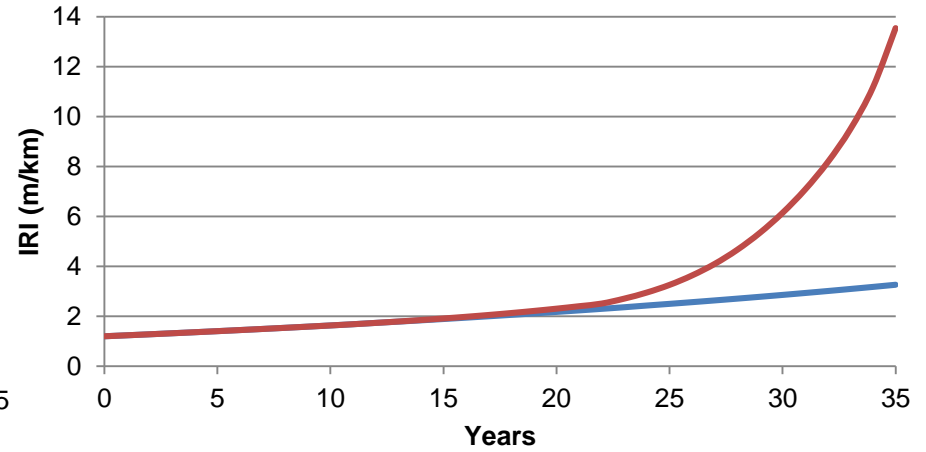
## Pavement strength



## Rutting



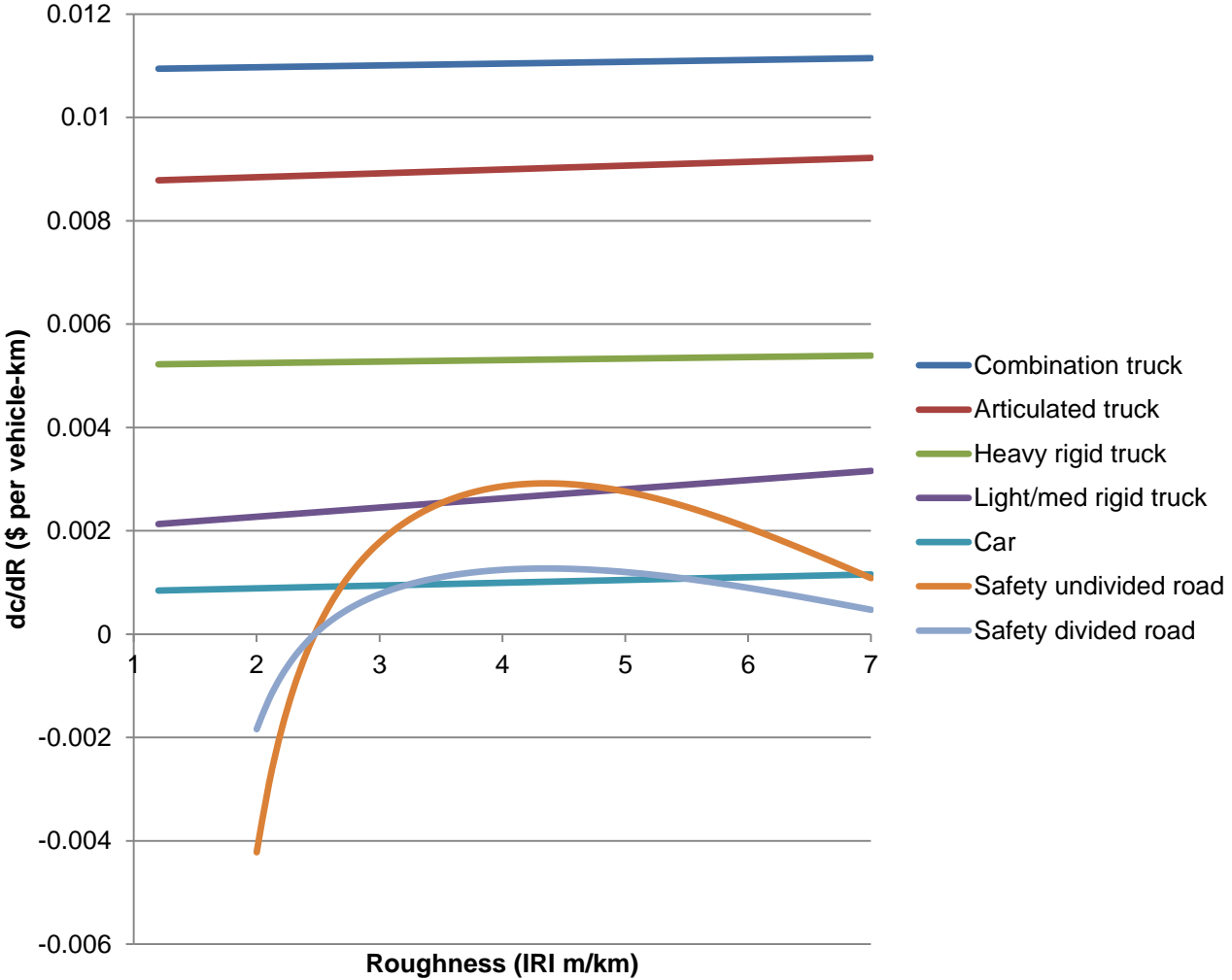
## Roughness



# Three treatment types

1. Resurface (overlay 10mm SS, 20mm AC)
  2. Resurface with shape correction (overlay 20mm SS, 40mm AC)
  3. Rehabilitation
- Each treatment type has
    - a cost per square metre
    - reset impacts on surface age, cracking, pavement age, pavement strength, rut depth and roughness.

# Road user costs: change w.r.t. roughness $\left(\frac{dc}{dR}\right)$

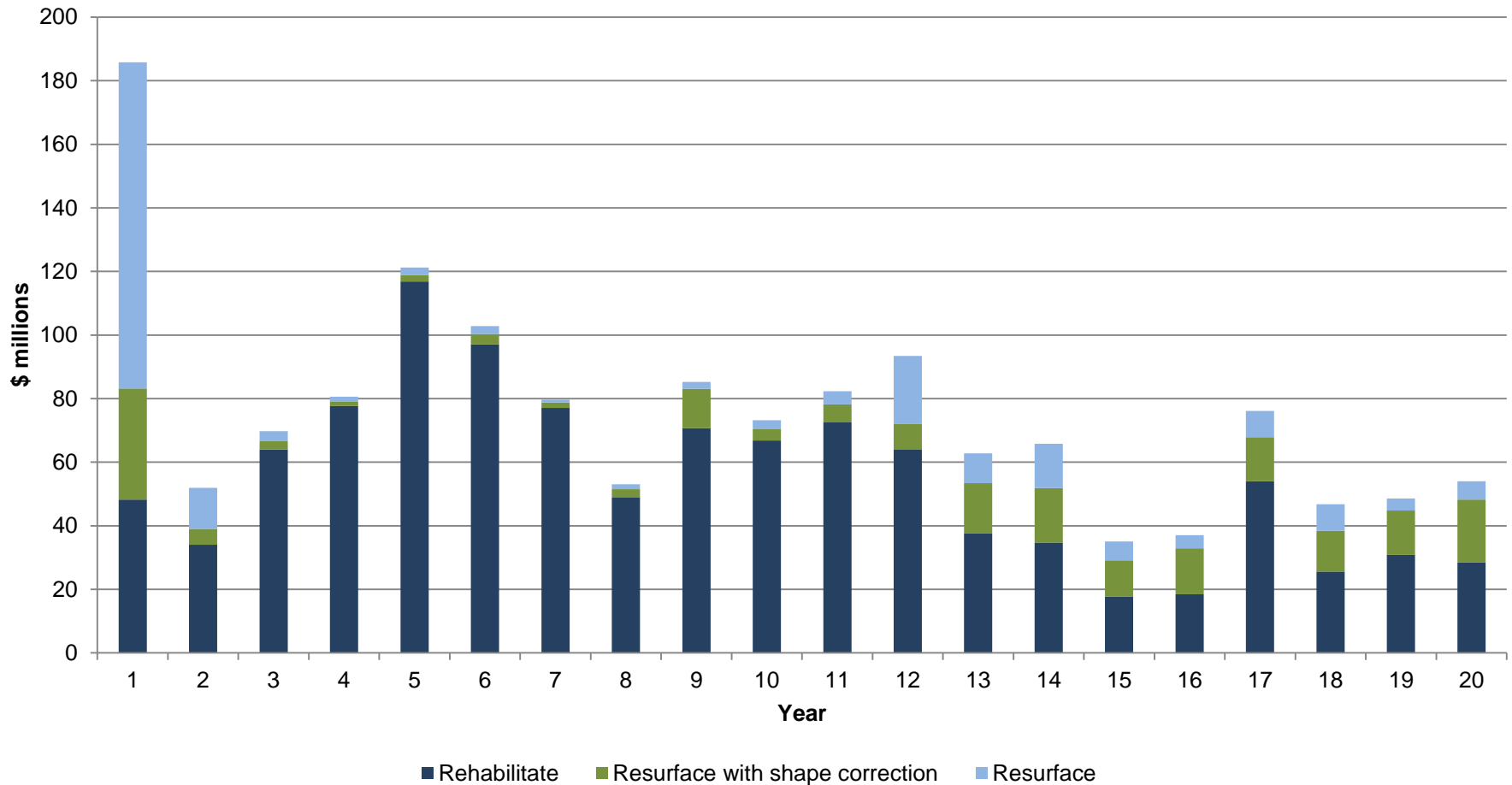


# Key model features

- 40 year analysis period
- 4% discount rate
- PVAC includes depreciation at the end of the analysis period (approximates continuation of the analysis period to infinity).
- Tests all combinations and timings of treatments with  $\geq 8$  years between treatments: 581,485 trials per segment
  - full enumeration of economically reasonable options
  - 2034 segments  $\times$  581,485  $\approx$  1.18b possible options tested
  - about two weeks runtime using Mathematica™ software parallel processing four segments at once.

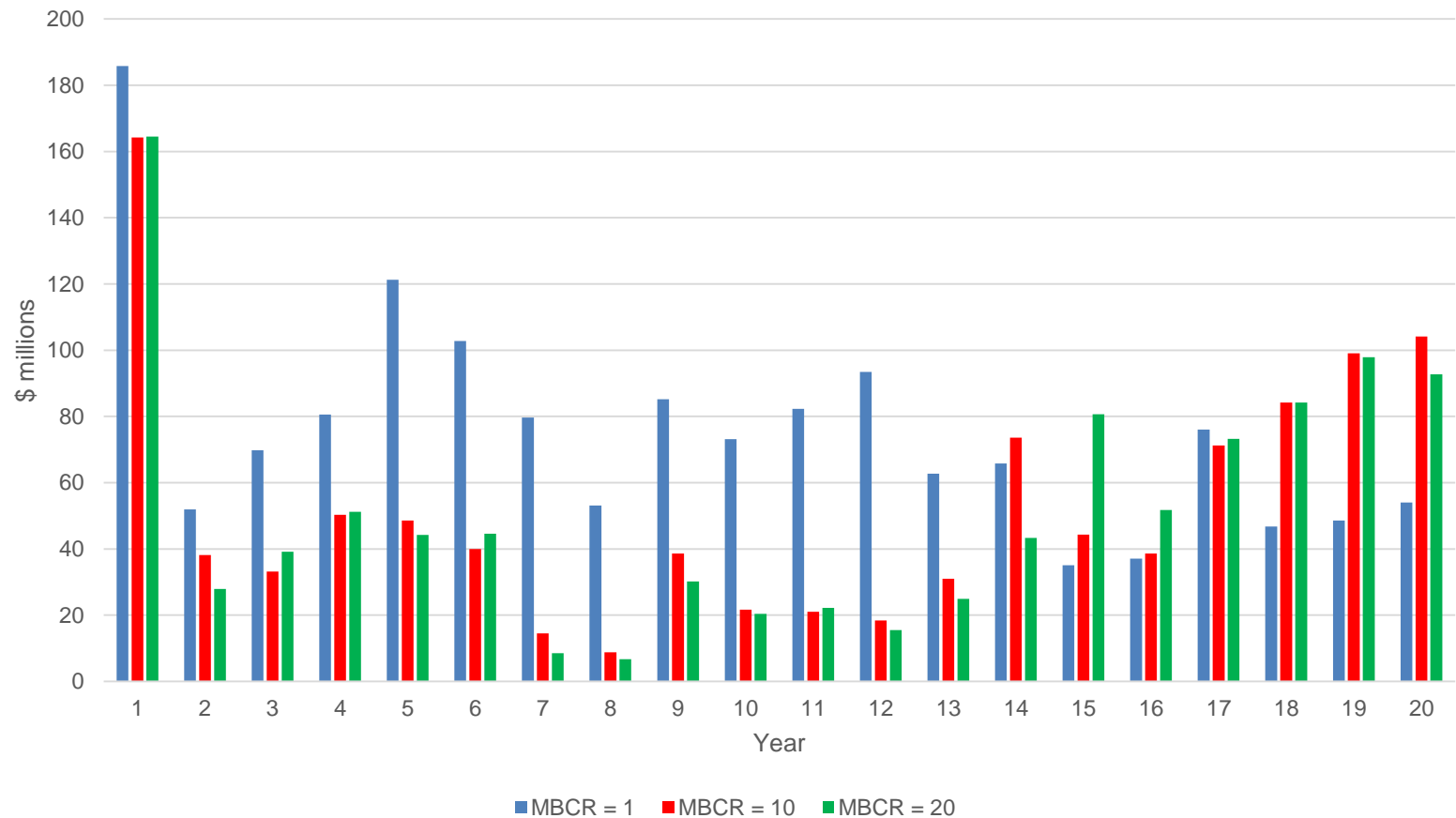
# Estimated optimal maintenance spending: unconstrained

Note the large spike in the first year to catch up the backlog, and jagged spending needs across other years. Not feasible physically or financially.



# Estimated optimal maintenance spending: target MBCRs of 1, 10 and 20

A target MBCR > 1 is equivalent to imposing a present value budget constraint.  
Still has a large spike in the first year and jagged spending across other years.



# Optimising with annual budget constraints

- Annual budget constraints are more realistic
  - because they smooth out spending over time.
- Need to consider all segments together to evaluate shifting scarce funds between segments
  - unlike a present value constraint where each segment can be considered in isolation.
- Too many combinations even for a genetic algorithm to find a good solution
  - 581,485 treatment type–time options to the power of 2034 segments  $\approx 10^{11,725}$  combinations.
- Three stage method developed.

# Annual budget constraint optimisation method: first stage

- Eliminate all non-dominated treatment options
  - Non-dominated options could never appear in an optimum solution
    - because they have a higher PVTTC for the same or higher agency costs in one or more budget-constrained years.
  - Reduces  $2034 \times 581,485 \approx 1.18\text{b}$  options tested to
    - 233,530 options for 20 budget-constrained years, and
    - 20,914 options for 10 budget-constrained years.



# Annual budget constraint optimisation method: second and third stages

**Second stage:** Choose from the set of non-dominated options for each individual segment  $i$  from 1 to  $n$ ,

- the option that minimises  $PVTT C_i + \sum_{t=1}^m \lambda_t c_{it}$
- subject to  $\sum_{i=1}^n c_{it} \leq B_t$  for each budget-constrained year from 1 to  $m$
- where
  - $\lambda_t$  = penalty factor or Lagrange multiplier for year  $t$
  - $c_{it}$  = cost of a treatment in year  $t$  on segment  $i$
  - $B_t$  = budget constraint for year  $t$

Evolver™ genetic optimisation software used to set  $\lambda$  values, one for each budget-constrained year (due to the ‘waterbed effect’).

**Third stage:** Refines the solution:

- Starting from the stage 2 solution, Evolver improves the solution by choosing between individual treatment options.
- Only makes a small improvement to the solution.

# Economic interpretation of penalty factor or Lagrange multiplier

- Gain in objective function from a unit relaxation of the annual budget constraint.

$$\lambda_t = - \frac{dPVTTC}{dB_t}$$

- In other words, the change in PVTTC from a one dollar increase in  $B_t$ , the budget for year  $t$ .

# Annual MBCR definition

MBCR<sub>*t*</sub> for year *t* is the saving in PVUC from increasing the budget in year *t* by an amount of one present-day dollar

$$MBCR_t = -\frac{dPVUC}{d\left[\frac{B_t}{(1+r)^t}\right]} = -\left\{\frac{dPVUC+dPVAC}{d\left[\frac{B_t}{(1+r)^t}\right]}\right\} + 1 = -(1+r)^t \frac{dPV TTC}{dB_t} + 1 = (1+r)^t \lambda_t + 1$$

where

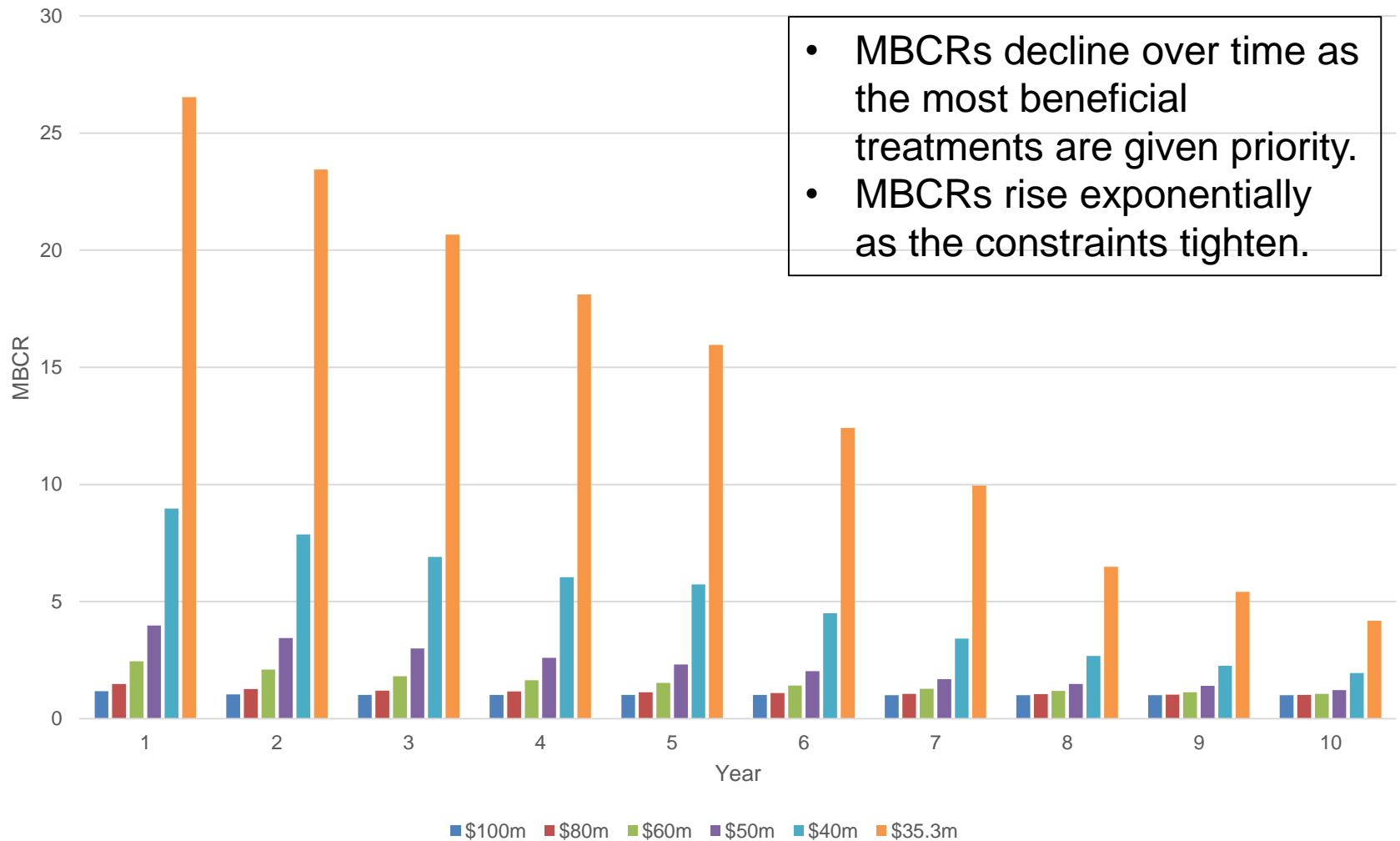
- *r* is the discount rate
- *dB<sub>t</sub>* is a one dollar increase in spending in year *t*, which has to be discounted to the present to use in the MBCR, hence
  - $d\left[\frac{B_t}{(1+r)^t}\right] = dPVAC$

Thus, we can estimate MBCR<sub>*t*</sub> from the penalty factor for year *t*.

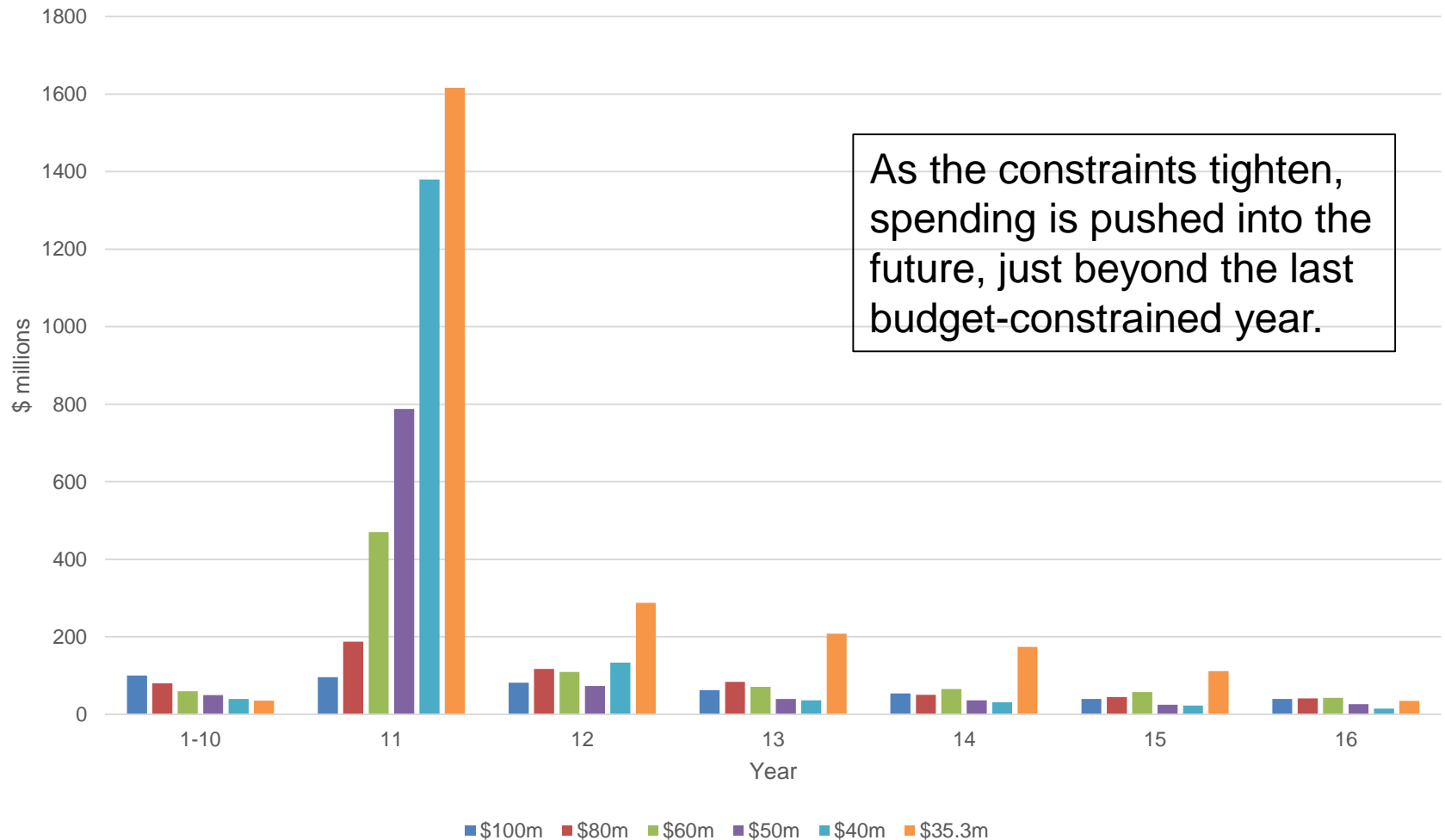
# Effects of uniform annual budget constraints

- First year MBCR highest, then MBCRs decline
- Maintenance spending pushed out into years after the constrained period
- 10-year uniform annual constraint: \$100m per annum
  - First-year MBCR = 1.2 (small cost to smoothing spending at this level)
  - Year 11 spending = \$96.0m (no backlog after constrained period)
- 10-year uniform annual constraint: \$35.3m per annum
  - minimum possible level for a 10-year constraint
  - First-year MBCR = 26.5
  - Year 11 spending = \$1.6b (large backlog of spending pushed out just beyond the constrained period)
- 20-year uniform annual constraints \$48.4m per annum
  - minimum possible level for a 20-year constraint
  - First-year MBCR = 21.4
  - Year 21 spending = \$1.0b

# Annual MBCRs with annual spending constraints for years 1 to 10

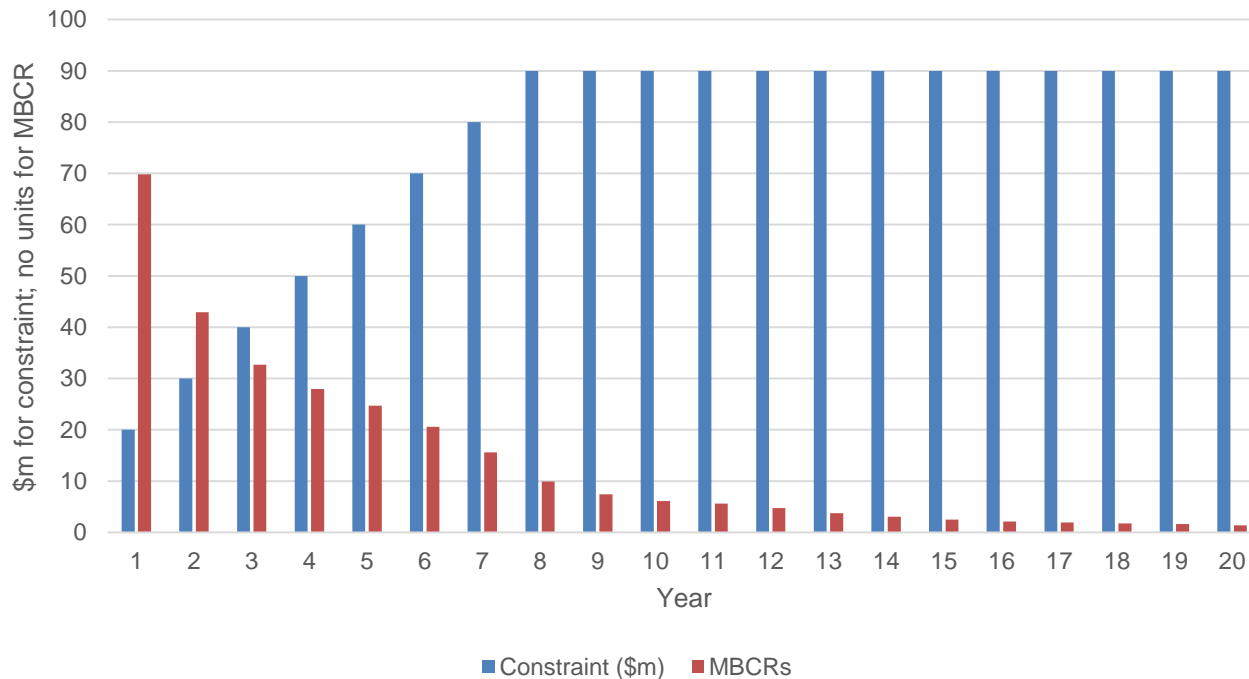


# Annual spending with annual spending constraints on years 1 to 10



# Example of rising budget constraints

- \$20m in first year, rising by \$10m each year to \$90m, then staying constant until year 20.
- First-year MBCR = 70, falling to 1.3 in year 20
- Year 21 spending = \$0.6b



# Annual incremental BCR definition

$$IBCR = \frac{-\Delta PVUC - \Delta PVAC + \Delta PVB}{\Delta PVB} = -\frac{\Delta PVTTTC}{\Delta PVB} + 1$$

- where  $\Delta PVB$  is the present value of a series of one or more annual budget increases of any feasible size.
- $\Delta PVB$  in numerator because  $\Delta PVAC$  includes  $\Delta PVB$ 
  - $-\Delta PVAC + \Delta PVB$  nets out to the PV of agency costs saved after the budget-constrained period.
- Formula reduces to previous present value budget constraint IBCR formula if  $\Delta PVAC = \Delta PVB$ .
- Approaches annual MBCR where  $\Delta PVB$  is for one year only and  $\Delta PVB \rightarrow 0$ .



# Example IBCR calculation

- Increase in 10-year uniform annual budget constraint from \$50m to \$60m.
  - PVTTC reduced by \$74m comprised of
    - \$43m reduction in PVUC and \$31m reduction in PVAC
      - (Note for tighter annual budget constraints, spending more in the short term **saves** road agency costs in present value terms)
  - PVB for first 10 years increased by \$81m.

$$IBCR = -\frac{\Delta PVTTC}{\Delta PVB} + 1 = -\frac{-\$74m}{\$81m} + 1 = 1.9$$

- Note: The IBCR of 1.9 is between the simple averages of the annual MBCRs over the 10 years
  - 1.6 average MBCR for the \$60m constraint, and
  - 2.3 average MBCR for the \$50m constraint.

# Some lessons learned

- The technique works better, the more detailed the data (reduces lumpiness)
  - as the penalty method treats a discrete problem as it were continuous.
- To avoid over-estimating MBCRs, it is important to find the lowest possible penalty ( $\lambda$ ) values that meet constraints
  - for example, set Evolver to minimise  $\sum_{i=1}^n PV TTC_i + 100 \sum_{t=1}^m \lambda_t$ .
- It is important to have a realistic spending profile over time, without a large spike after the constrained period ends
  - for example, gradually rising from the current spending level to a sustainable level.

# A qualification

- The methods developed in the present study do not allow for technological innovations and improved maintenance practices stimulated by budget-constrained circumstances.

# Value of the technique

- Can present decision makers with a variety of options with different spending profiles over time with information on
  - the value of small spending changes in individual years using MBCRs, and
  - the comparative value of different spending profiles using IBCRs.
- The MBCRs and IBCRs can be compared with BCRs for capital projects.