Capacity and Flexibility of Transportation Systems

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Outline

Motivation

Conceptual definition

Measurement: Desirable features

Issues

Model

Application

- Capacity
- Flexibility

Capacity

Motivation

- Traffic growth vs infrastructure (last 30 years):
  - Domestic freight ton-km + 64%, international +93%
  - track-km - 34%, hwy. lane-km + 43%
  - Projections to 2020: dom. +87%, int. +107%
  - National issue: TRB sessions, NRC policy studies, press coverage, etc.
- Important concept: capacity explains phenomena
- Interesting questions: How to define, measure?
- Potentially applicable to other network systems

System Capacity & Flexibility Literature

- Capacity
  - Morlok 1980 - Conceptual
  - Clarke 1995 - Simulation model - Rail network
  - Morlok and Riddle 1999 - Optimization model - rail capacity
  - Wong and Yang 1997 - User equilibrium - road network
  - Yang et al. 2000 - Continued
- Flexibility in other fields
  - Jordan and Graves, 1995- Process flexibility - product mix and quantity
  - Vokurka and O'Leary-Kelly, 2000- Manufacturing flexibility related to exogenous variables
  - Feitelson and Salomon, 2000- Qualitative network flexibility features and impacts

Definition

System capacity is the maximum traffic throughput that can be sustained subject to

- The physical system (assets)
- Supplies and other resources (e.g. labor) available
- Environmental, other regulatory limitations
- Level of service
- Financial viability

Desired Features

- Quantitative
- Unique value
- Estimation procedure efficient
- Use data that is available or could reasonably be obtained
- Objective
- Incorporate stochastic elements

Heterogeneity of Traffic

Fix mix of traffic by OD and commodity

- Can be base (actual) traffic, or other
- Cargo (i,j,k) = Fraction(i,j,k) x Total cargo

$$\sum \text{Fraction}(i,j,k) = 1$$

The MAXCAP Model

- Network model
  - Facilities — Vehicle and cargo flows
  - Resources — Emissions
- Objective: Maximize overall traffic
- Limitations
  - Fleet — Energy
  - LOS — Cost, etc.
  - Traffic pattern (spatial, commodity mix)

MAXCAP Model

(1) $$Max Z_m = \sum_{r=1}^{R} x_r$$

subject to

(2) $$x_r = \alpha_r \cdot [\sum_{r=1}^{R} x_r], \forall r$$

(3) $$\sum_{p \in P_r} \phi_p \cdot y_p^1 = x_r, \forall r$$

(4) $$\sum_{p \in B_a} (y_p^1 + y_p^2) \le \gamma \cdot w_a, \forall a$$

(5) $$w_a \le \beta \cdot v_a, \forall a$$

(6) $$v_a \le K_a, \forall a$$

(7) $$\sum_{p \in D_n} [y_p^1 + y_p^2] \le L_n$$

(8) $$\sum_{a=1}^{A} [T_a \cdot w_a] \le H_{car}$$

(9) $$\sum_{p=1}^{P} [S_p \cdot (y_p^1 + y_p^2)] \le H_{con}$$

(10) $$\sum_{a \in E_n} w_a = \sum_{a \in L_n} w_a, \forall n$$

(11) $$\sum_{a \in F_n} (y_p^1 + y_p^2) = \sum_{a \in M_n} (y_p^1 + y_p^2), \forall n$$

Maximize Total System Cargo Traffic:
Max TOTCARGO= SUM CARGO (LANE)

Traffic Pattern:
CARGO (LANE) = ALPHA (LANE) * TOTCARGO

Arc Vehicle and Cargo Flows:
AVLD (LANE) * LDCNTR (LANE) = CARGO (LANE)
CARVOL (ARC) ≥ (LDCNTR (LANE)+MTYCNTR (LANE))/CARCAPY
TRAINVOL (ARC) ≥ CARVOL (ARC)*CARLNTH/MAXTRAINLNTH (ARC)

Link Capacity:
TRAINVOL (ARC) ≤ TRAINCAP (ARC)

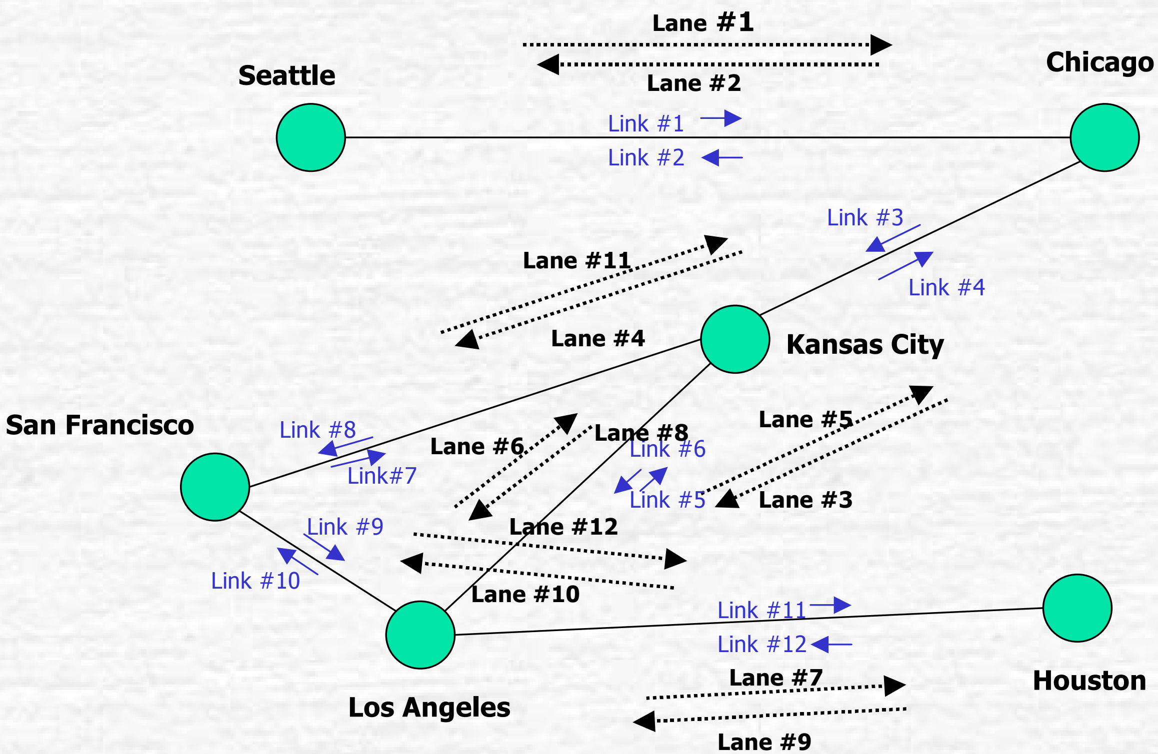
Terminal Capacity:
SUM (LDCNTR (LANE)+MTYCNTR (LANE)) ≤ LIFTCAP (TERM)

Fleet Size:
SUM (SUM CARTIME (ARC) * CARVOL (ARC)) ≤ CARFLTHRS
SUM CNTRTIME(LANE)*(LDCNTR (LANE)+MTYCNTR (LANE)) ≤ CNTRFLTHRS

Conservation of Flow:
SUM CARVOL (ARC)) = 0
SUM (LDCNTR (LANE)+MTYCNTR (LANE))= 0

MAXCAP Application

Application Series 1: Western DSS Network



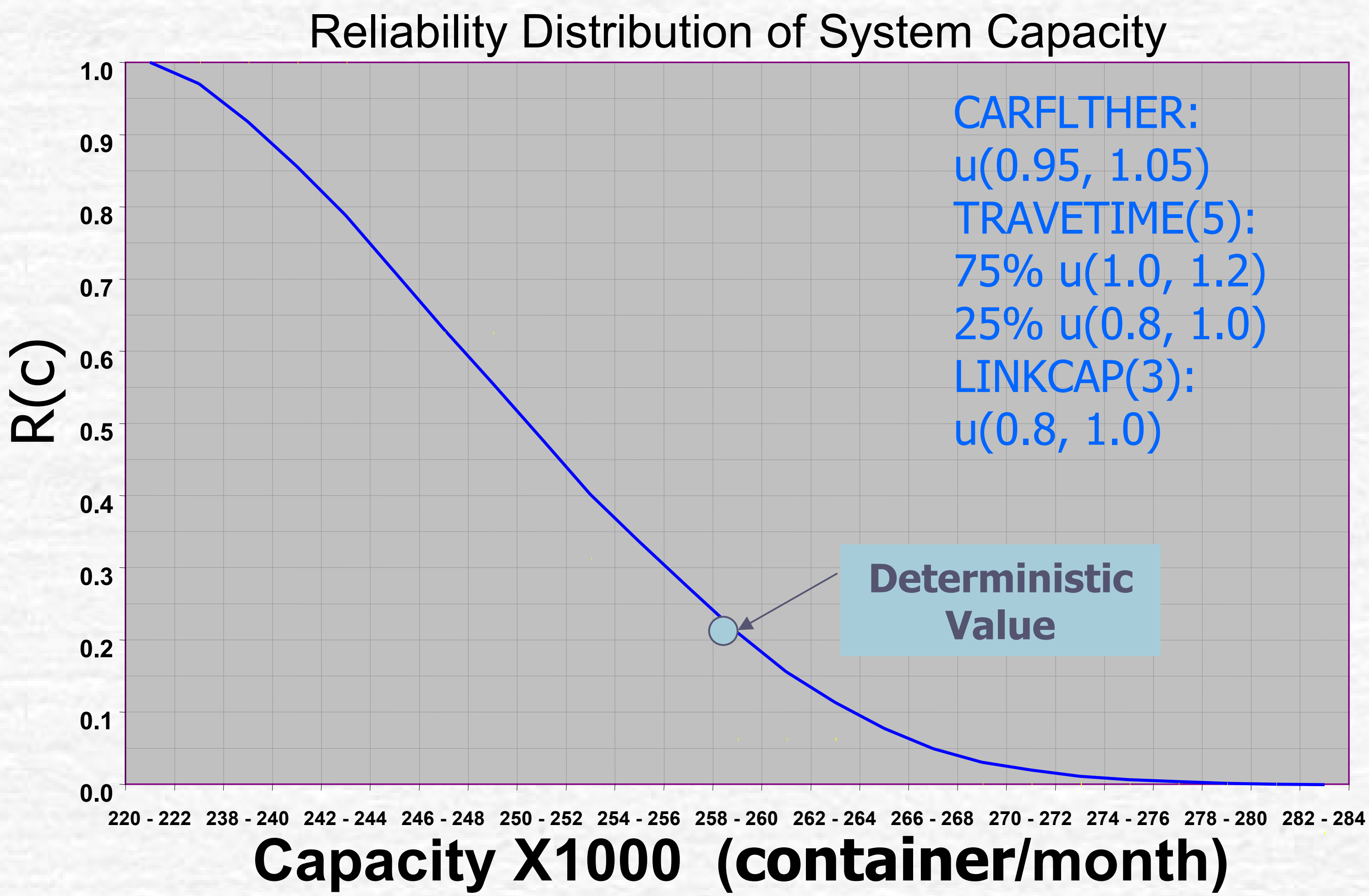
Base Traffic = 201,000 containers/month
Deterministic System Capacity (Z) = 259,000 cont./mo.
Reserve Capacity = 58,000 cont./mo. , a 28% increase

System Capacity Results

- Deterministic Model
  - Base = 201,000 cont./mo.
  - Capacity (Z) = 259,000 cont./mo.
  - Reserve Capacity = 58,000 cont./mo. , or 28%
- Stochastic Model
  - Cap Prob (95%) = 248,000 cont./mo., or 23%
  - Cap Prob (50%) = 251,000 cont./mo.
  - Very different!

Example of Results - Reliability Algorithms

3 Random parameters: car fleet size, a link capacity, and a link travel time



Example of Results - Reliability Algorithms

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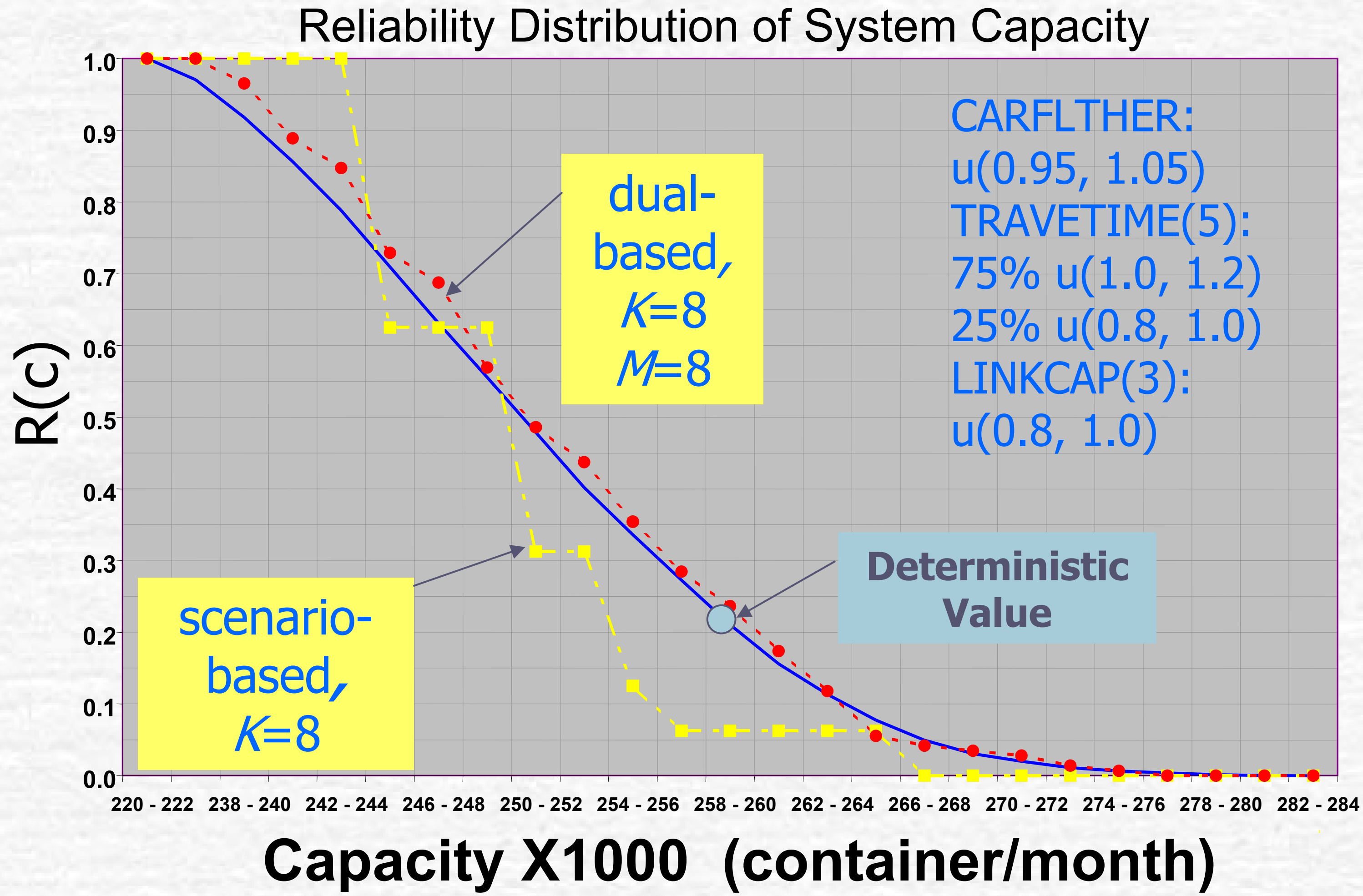


The ADDCAP Model

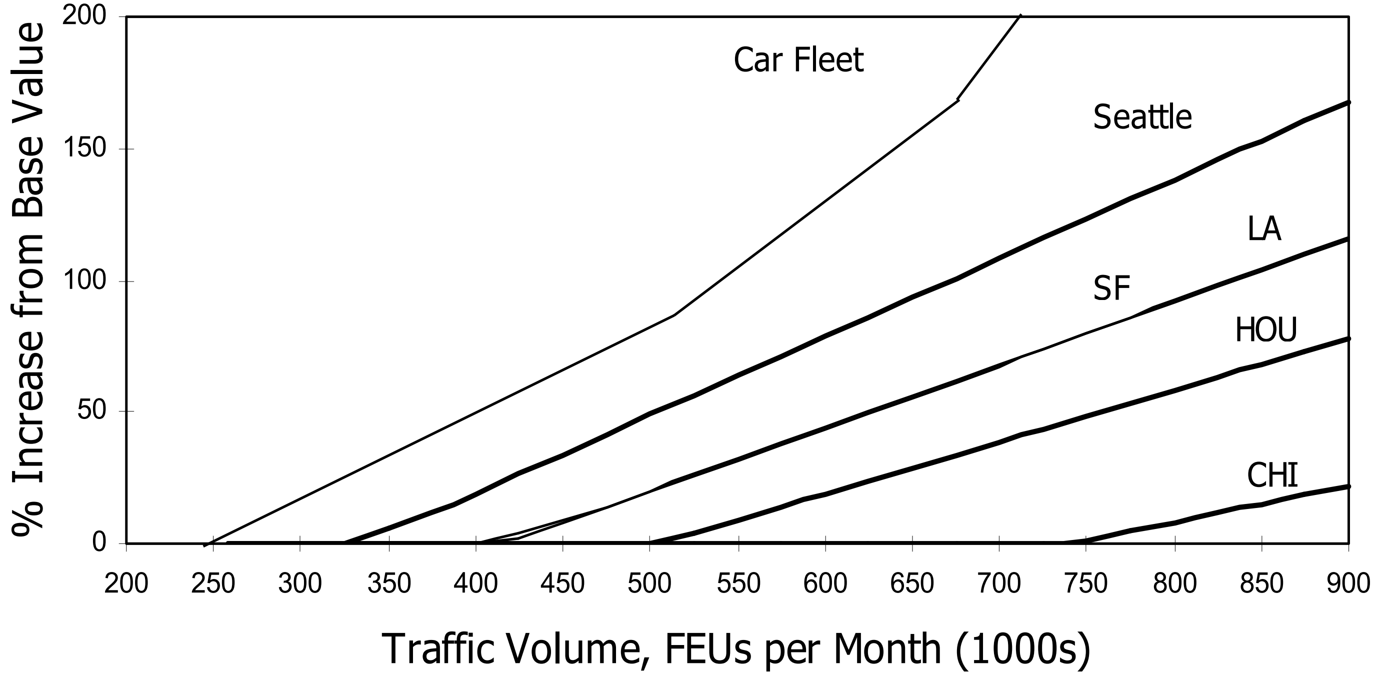
Minimize: Facility Capacity and Fleet Additions

Subject to:

- Specified increase in system traffic
- Traffic pattern
- Limitations
  - Facility capacity, fleet, LOS
  - Others

ADDCAP Results

Additional Fleet and Terminal Capacity Needed



Conclusions

- Can define System Capacity
- Deterministic approach
  - Plausible measures
  - Data requirements reasonable
- Stochastic analysis critical: Capacity Reliability
  - Heuristics very effective compared to Monte Carlo simulation
  - Estimation requires data and information not currently available

Flexibility

Motivation

- Uncontrolled factors change
  - Traffic volumes and patterns
  - Level of service needs, preferences
- Transport plant seemingly immovable
- Needed for system to perform well
- Interesting questions: how to define, measure?

Flexibility

Definition: Flexibility refers to the ability of the system to adapt to external changes while maintaining an adequate level of performance.

Examples:

- External changes (in system's environment):

  Changes in trade patterns, traffic levels, LOS requirements, cost of resources, fuel availability, regulations

- Performance measures

  ROI, revenue and cost, user satisfaction (LOS), environmental impacts

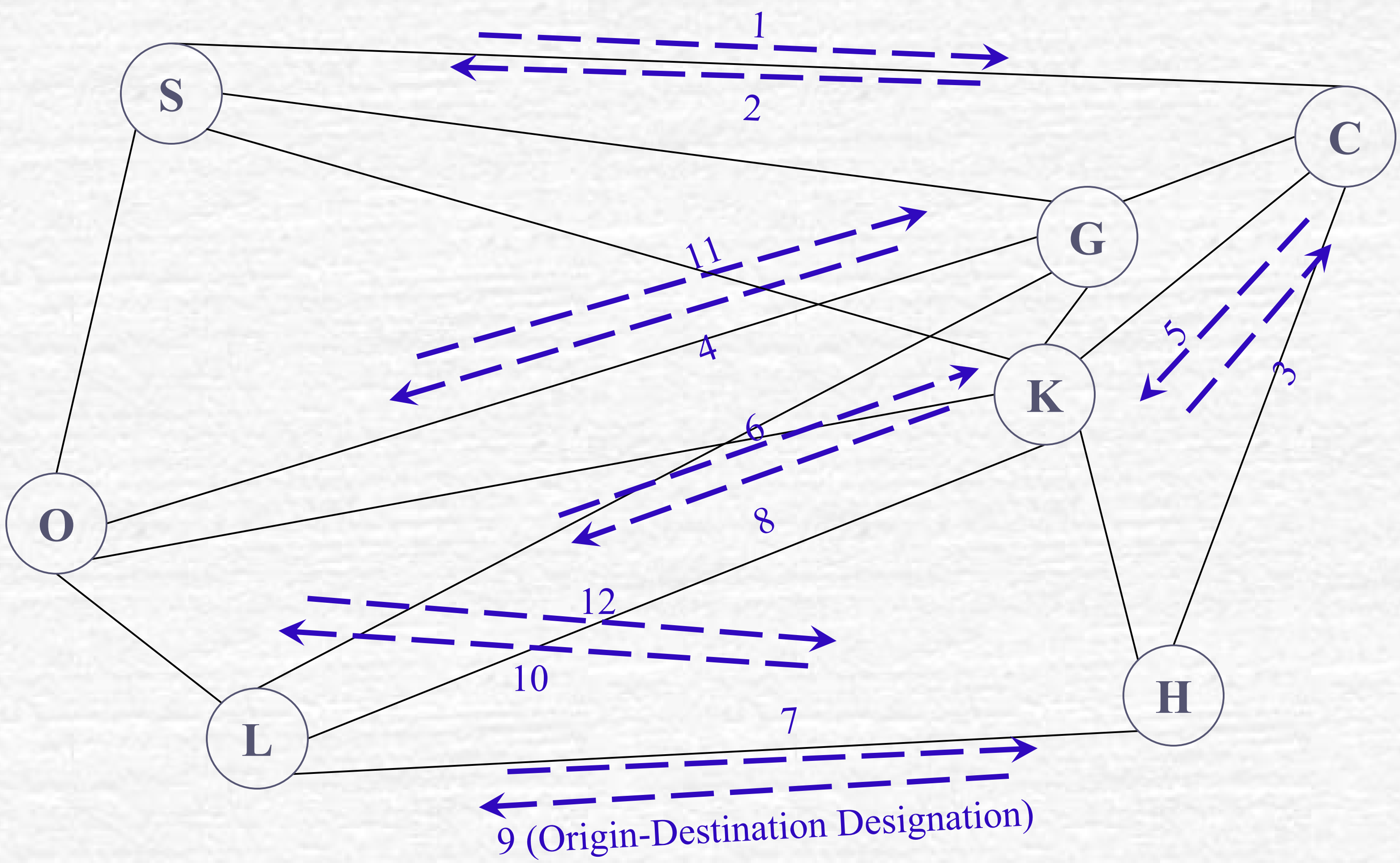
Measuring Flexibility of Capacity

(to accommodate increased traffic and pattern shifts)

MAXCAP: Estimates the maximum traffic that can be accommodated by the system subject to an underlying traffic pattern (unit OD matrix).

ADDVOL: Estimates the maximum demand accommodated by the system while permitting deviations from the base traffic pattern. Deviations can be limited or constrained by various methods.

Test Network: DSS Container System



Routing Options

- Shortest Path (between OD pairs) - Only 1 path to route traffic
- Shortest + 1 Node Disjoint Paths - A shortest path and a second shortest path which uses none of the arcs of the shortest path
- Level of Service Paths - All paths (between OD pair), with travel time/distance less than or equal to the 1 Node Disjoint Path. Use of the same arcs and nodes is allowed.

MAXCAP Results

Path Options	Capacity, (FEUs/Month)	% Increase over 1987 Traffic	% Increase over SP
Shortest Path (SP)	147887	28.6%	0.0%
Shortest + 1 Node Disjoint Paths (SP+1)	320610	178.8%	116.8%
Level of Service Paths (LOS)	335865	192.1%	127.1%

- Base: 1987 traffic volume- 1.15x10^5 Containers/Month
- Any and all lanes (OD) could increase traffic by
  - Shortest path option --> 28.6%
  - Shortest +1 node disjoint paths option --> 179.2%
  - Level of service paths option --> 192.2%
- Considerable demand flexibility
- Increasing path options increases flexibility

ADDVOL Model

- **MAXCAP:** max $Z_m = \sum_{r=1}^{R} X_r$

  Subject to Traffic Pattern (TP, unit OD Matrix) constraint

- **ADDVOL:**
  - **Base: Eliminate TP restrictions**

    $$\max Z_{B1} = \sum_{r=1}^{R} \left(X_r + \bar{x}_r \right)$$

  - **Incremental: Limit lane increase by a percentage of the MAXCAP solution:**

    $$\max Z_{B2} = \sum_{r=1}^{R} \left(X_r + \bar{x}_r \right) \qquad \theta \cdot X_r \geq \bar{x}_r, \forall r \qquad \theta \equiv \text{given value, e.g. 20\%}$$

  - **Penalty: on deviations from the TP:**

    $$\max Z_{B3} = \sum_{r=1}^{R} \left(X_r + \bar{x}_r \right) - \beta \cdot \sum_{r=1}^{R} \left[\frac{\left(X_r + \bar{x}_r \right) - \left(\frac{X_r}{Z_m} \cdot \sum_{r=1}^{R} \left[X_r + \bar{x}_r \right] \right)}{Z_m} \right]^2$$

    Capacity — Penalty Function

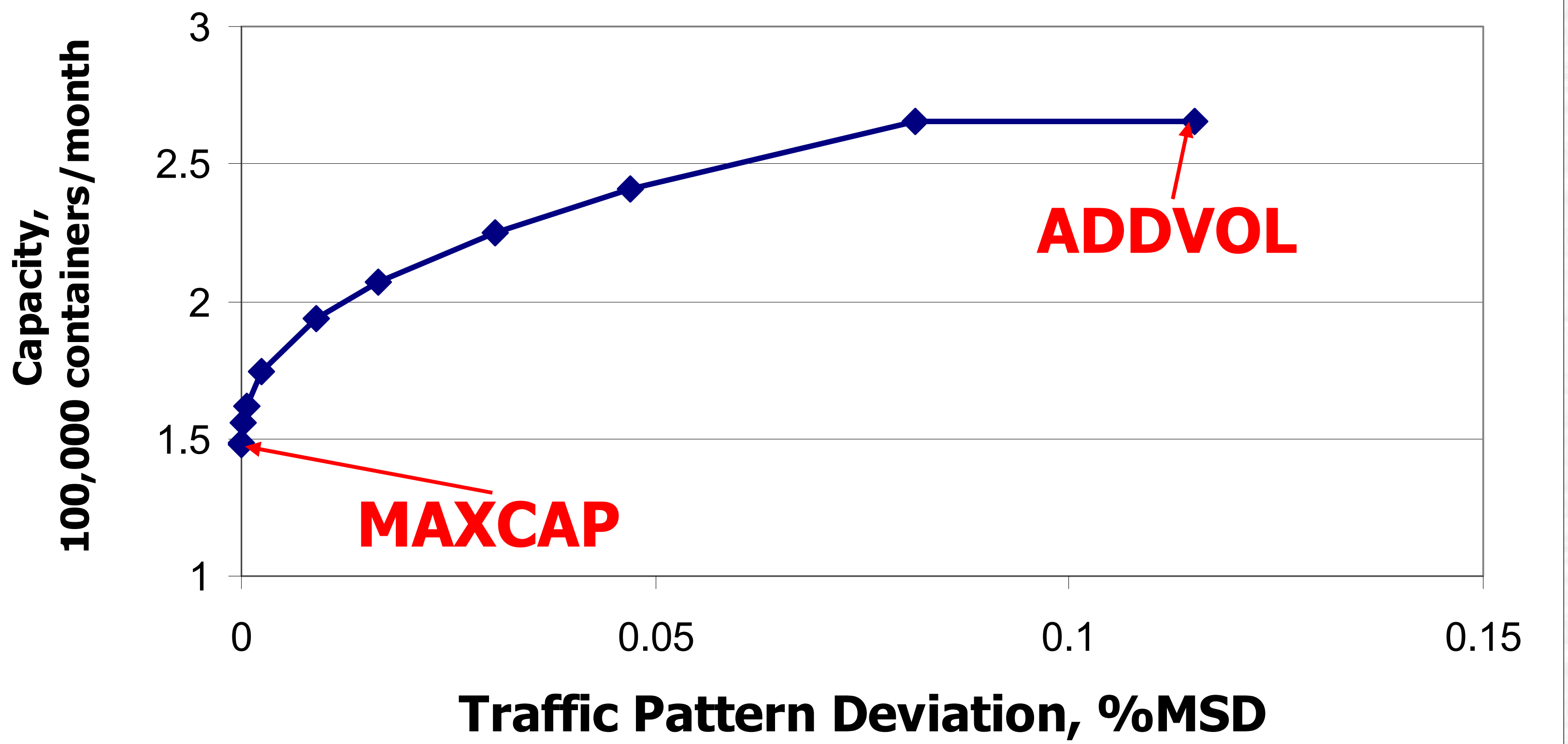
MAXCAP & ADDVOL Base Results

(SP Routing Option)

Traffic Lane	MAXCAP Estimate (FEU/Mo)	ADDVOL Estimate (FEU/Mo)	MAXCAP Increase over 1987 Traffic (FEU/Mo)	ADDVOL Increase over 1987 Traffic (FEU/Mo)	ADDVOL % Increase over 1987 Traffic
1	19817	42000	4407	26590	172.6%
2	18042	42000	4012	27970	199.4%
3	27951	31648	6216	9913	45.6%
4	10352	10352	2302	2302	28.6%
5	32683	32683	7268	7268	28.6%
6	5176	9317	1151	5292	131.5%
7	6063	9545	1348	4830	102.4%
8	5176	9317	1151	5292	131.5%
9	7986	10580	1776	4370	70.4%
10	3549	28937	789	26177	948.5%
11	9317	9317	2072	2072	28.6%
12	1775	29973	395	28593	2071.9%
Total	147887	265668	32887	150668	131.0%

Note: The MAXCAP % increase over 1987 Traffic is a constant (28.6%)

Capacity vs. Traffic Pattern Deviations

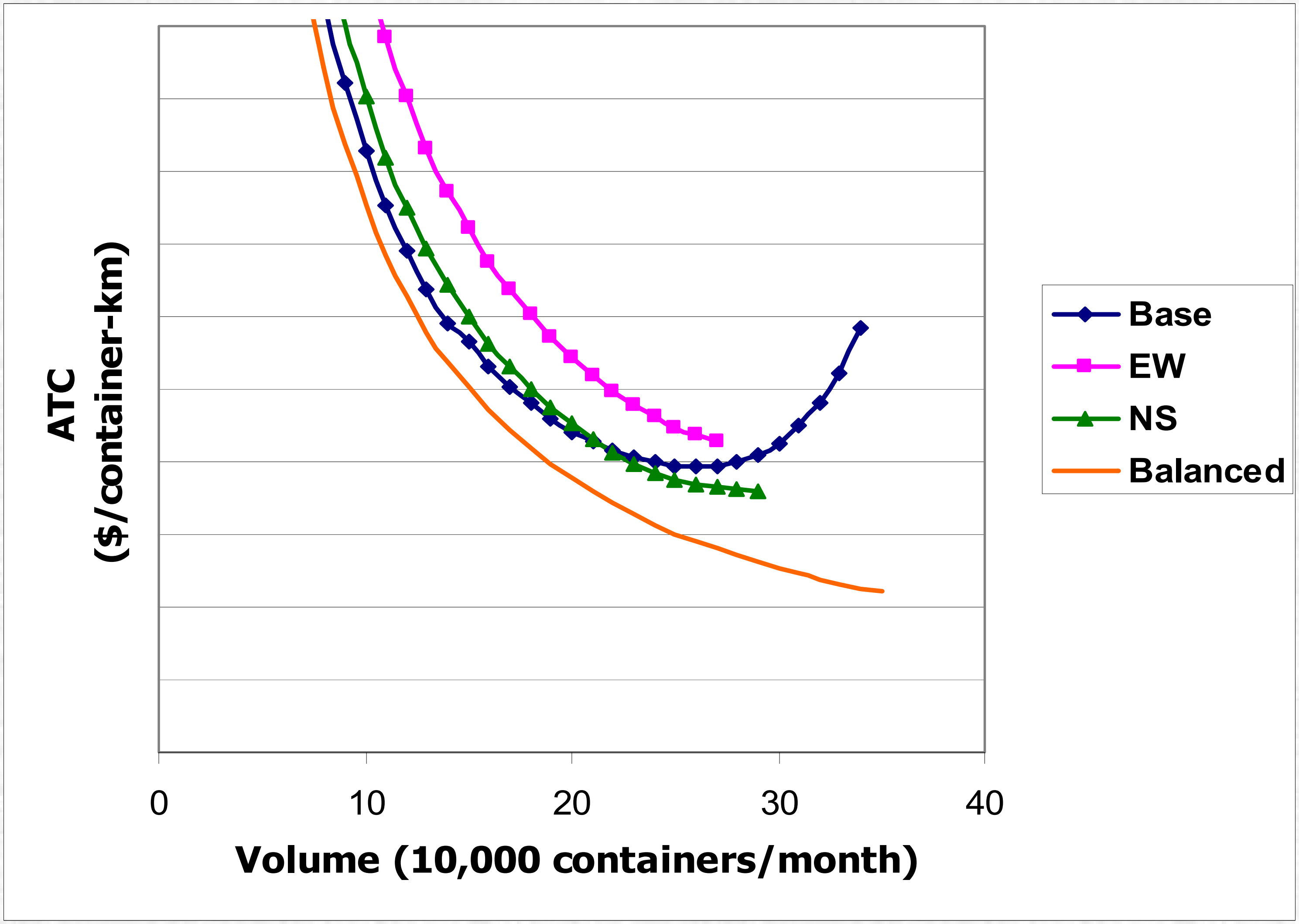


$$\%MSD = \sum_{r=1}^{R}\left[\frac{\left(X_r+\bar{x}_r\right)-\left(\frac{X_r}{Z_m}\cdot\sum_{r=1}^{R}\left[X_r+\bar{x}_r\right]\right)}{Z_m}\right]^2$$

Comparison of MAXCAP, ADDVOL, and ADDVOL at 100% Limit

Path Options	MAXCAP Estimate (FEUs/Month)	ADDVOL Estimate (FEUs/Month)	ADDVOL at 100% Limit (FEUs/Month)	% of ADDVOL estimate at 100% Limit
Shortest Path (SP)	147887	265668	217099	82%
Shortest + 1 Node Disjoint Paths (SP+1)	320610	409291	375215	92%
Level of Service Paths (LOS)	335865	412124	385118	93%

ATC vs. Volume - Different Flow Patterns



Conclusions

- Workable conceptual definition of System Flexibility
- Considered one application: capacity or demand flexibility.
- Two resulting models
  - Operational: data, computation standpoint
  - Yield unique measurements of feasibility of system-wide traffic volume changes.
  - Results of trial application appear plausible.
- Only a start
  - Are these useful measures?
  - Is flexibility important?

Stochastic Model: System Capacity Reliability

Deterministic Optimization Model

$$\text{Max } z = \sum_{p=1}^{P} x_p$$

subject to

$$x_p = \alpha_p \cdot [\sum_{p=1}^{P} x_p], \forall p$$

$$\phi_p \cdot y_p^1 = x_p, \forall p$$

$$\sum_{p \in B_l} (y_p^1 + y_p^2) \le \gamma \cdot w_l, \forall l$$

$$w_l \le \beta \cdot v_l, \forall l$$

$$v_l \le L_l^c, \forall l$$

$$t_l^w = f(v_l), \forall l$$

$$t_p^c = \sum_{l \in A_p} [t_l^w + t_l^n], \forall p$$

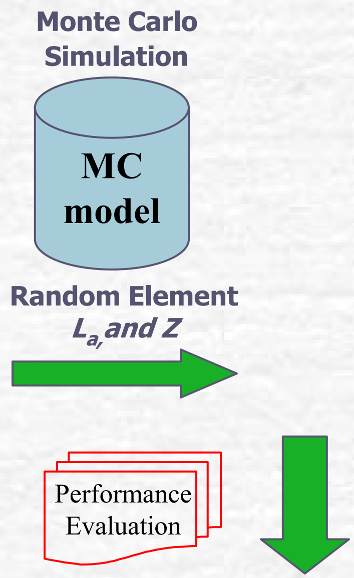
$$\sum_{p \in D_n} [y_p^1 + y_p^2] \le L_n^c$$

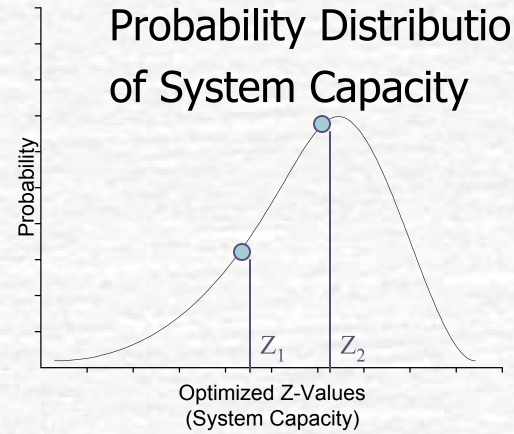
$$\sum_{l=1}^{L} [t_l^w \cdot w_l] \le H_{car}$$

$$\sum_{p=1}^{P} [t_p^c \cdot (y_p^1 + y_p^2)] \le H_{con}$$

$$\sum_{l \in E_n} w_l = \sum_{l \in L_n} w_l, \forall n$$

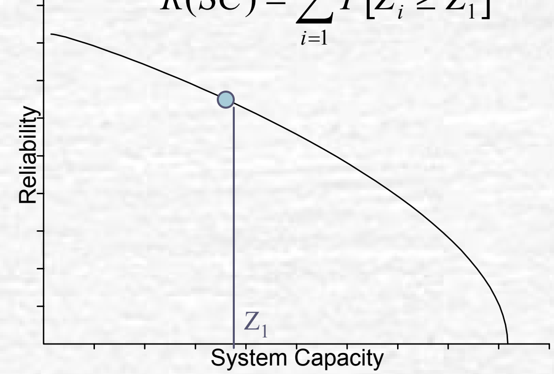
$$\sum_{l \in F_n} (y_p^1 + y_p^2) = \sum_{l \in M_n} (y_p^1 + y_p^2), \forall n$$





Cumulative Reliability of System Capacity

$$R(SC) = \sum_{i=1}^{n} P[Z_i \ge Z_1]$$



Why *System* Capacity?

- Natural to focus on links and nodes
  - Visible bottlenecks usually at few locations
  - Know how to assess and alleviate these
- But many limitations are system wide, e.g.,
  - Energy
  - Labor
  - Fleet
  - Area emissions
- Traffic can be routed throughout system
  - Routes interact over entire system