Economics of Network Growth

Radcliffe Exploratory Seminar on Dynamic Networks:
Behavior, Optimization and Design

October 20-21, 2006, Radcliffe Institute, Cambridge MA

David Levinson
University of Minnesota &
Imperial College

NEXUS

Acknowledgements

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  - Wei Chen
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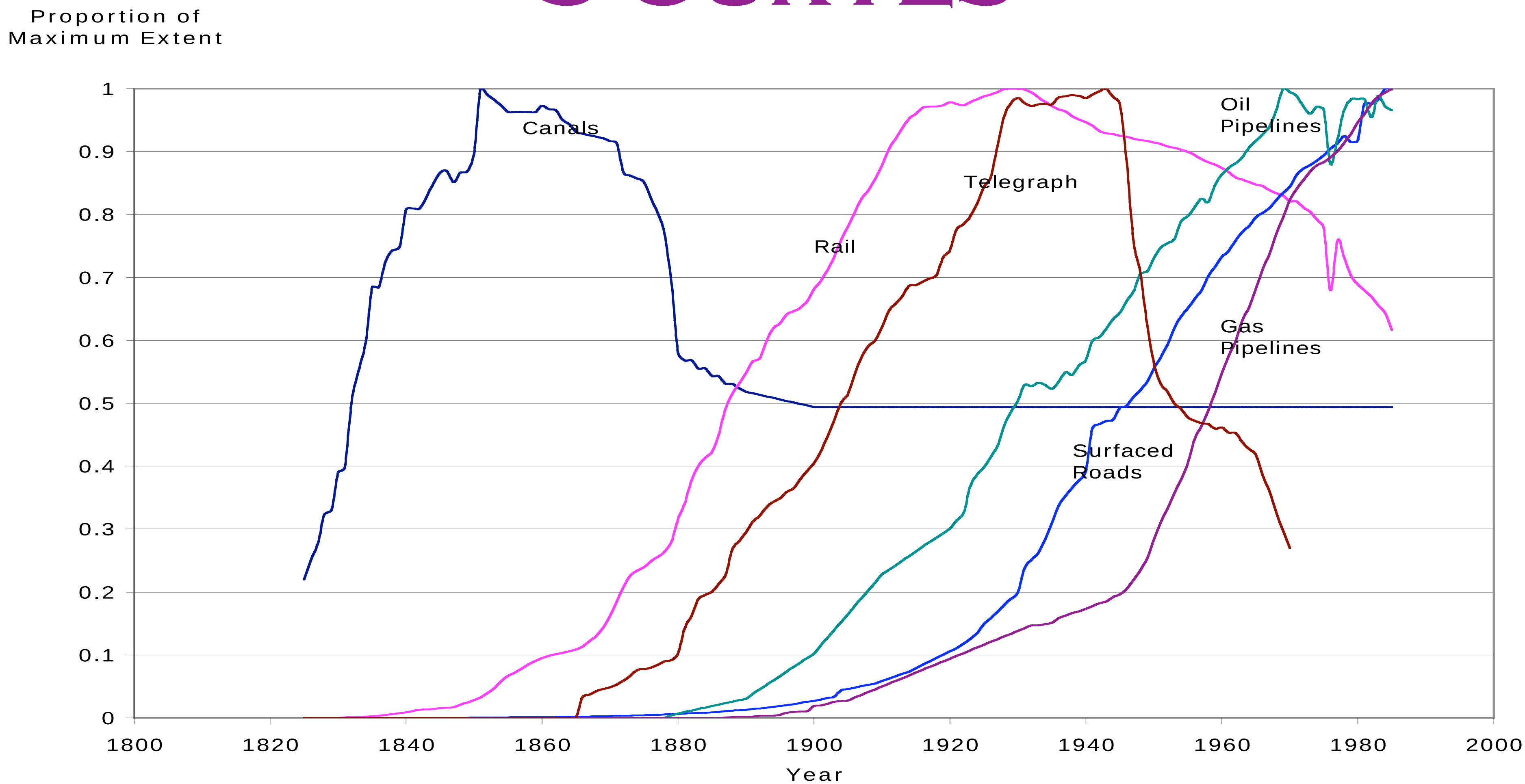
S-Curves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2000
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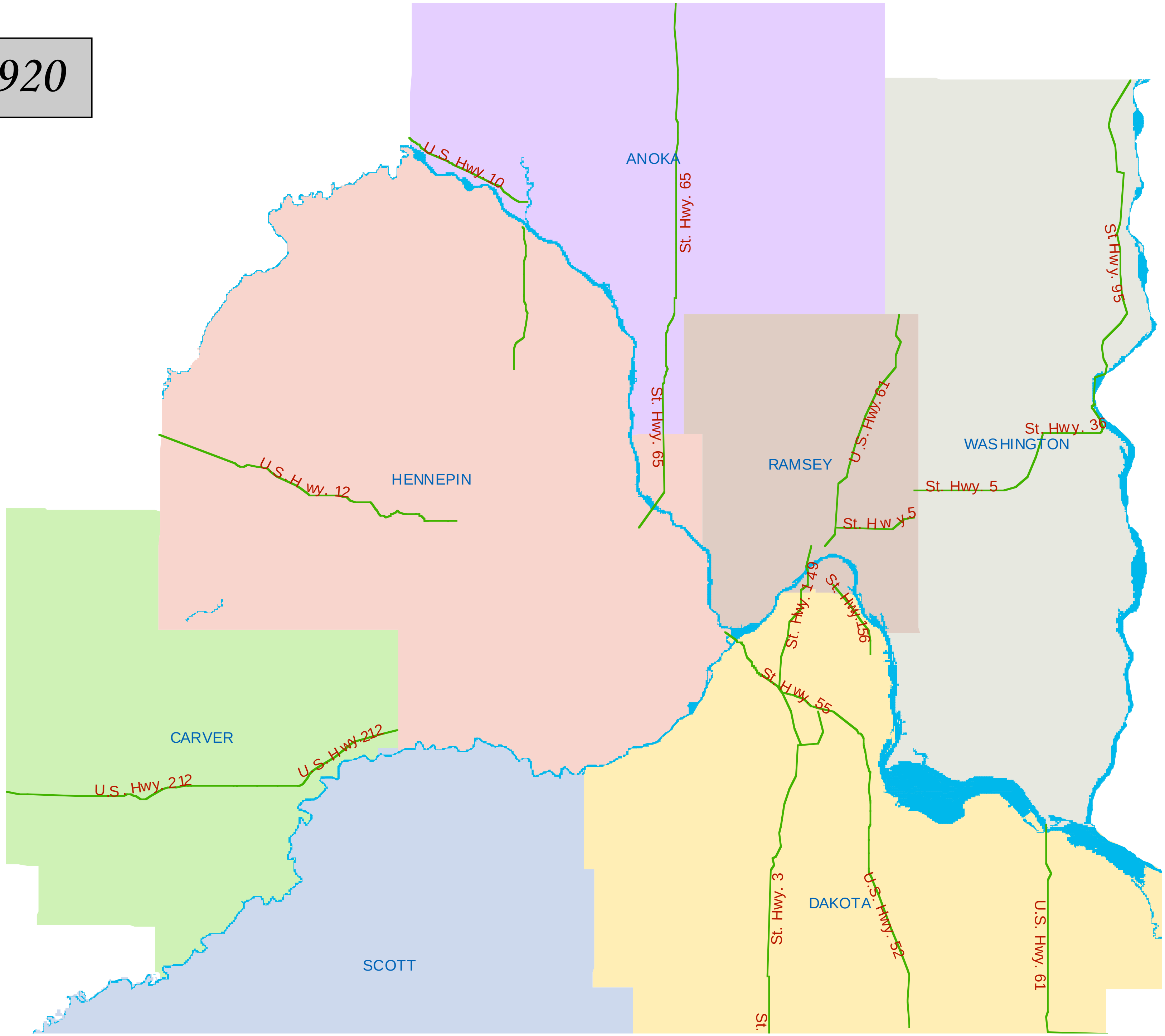
LEGEND

	Interstate
	Undivided Highway
	Divided Highway
	No Construction Log

1920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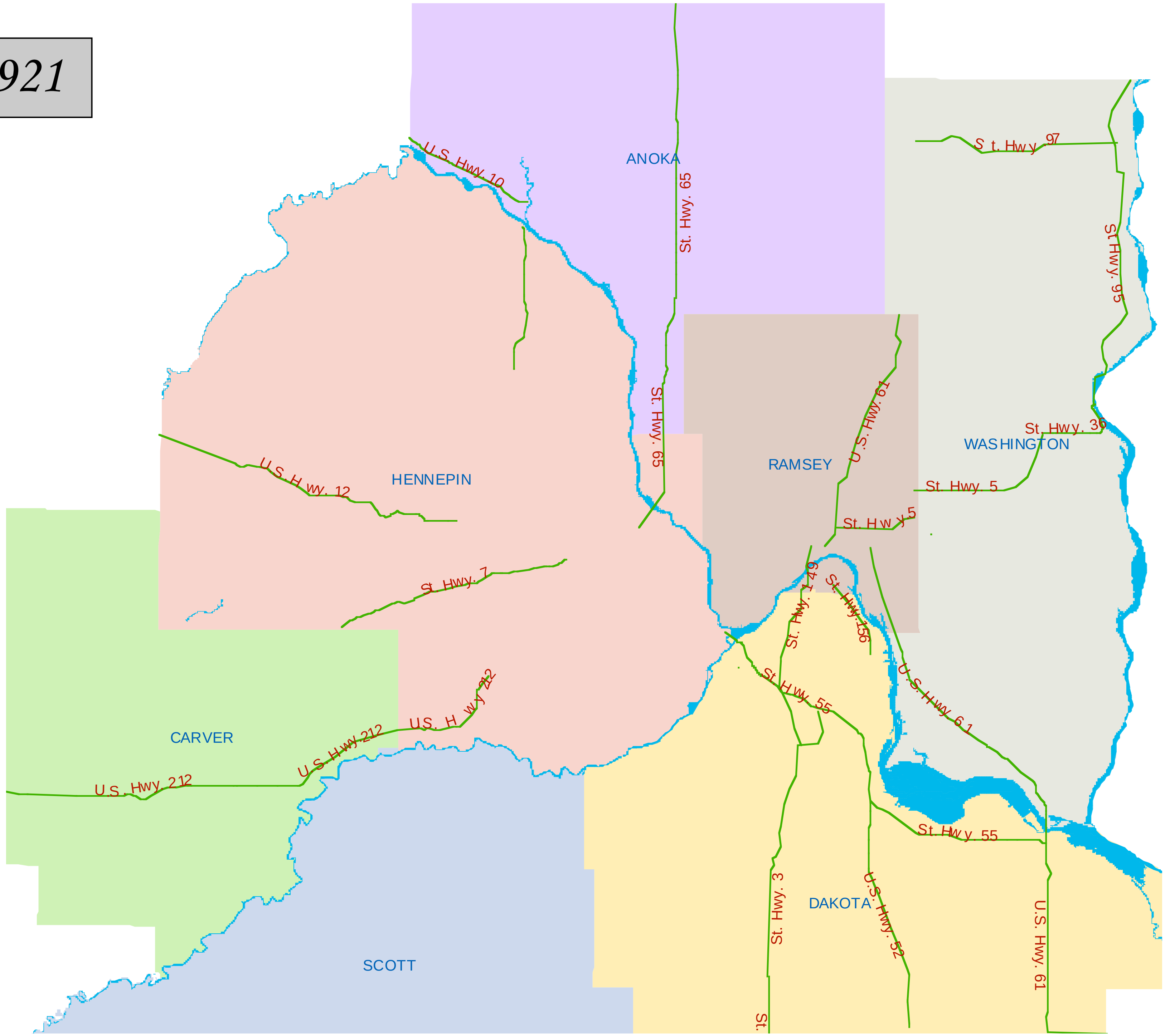
1921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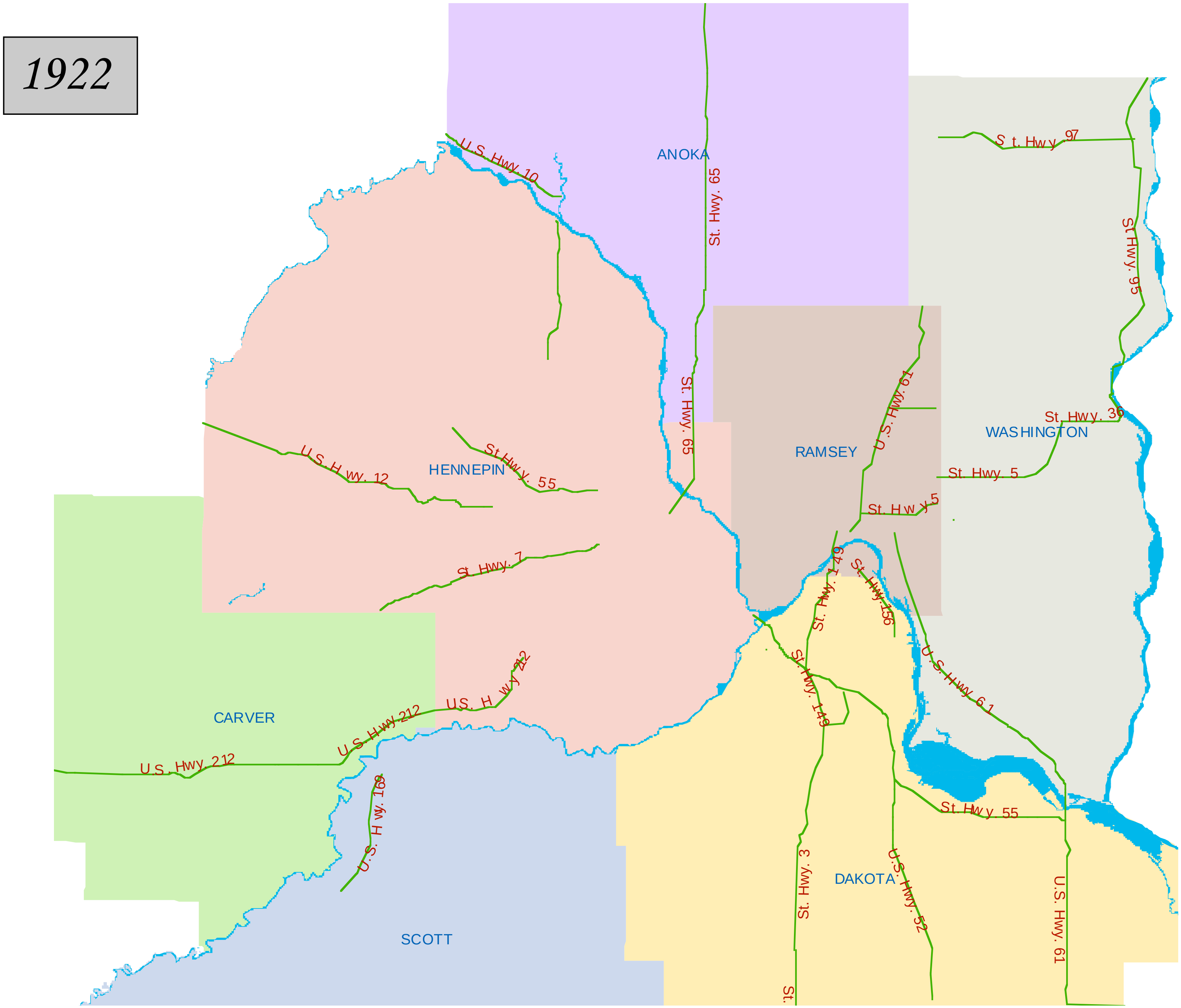
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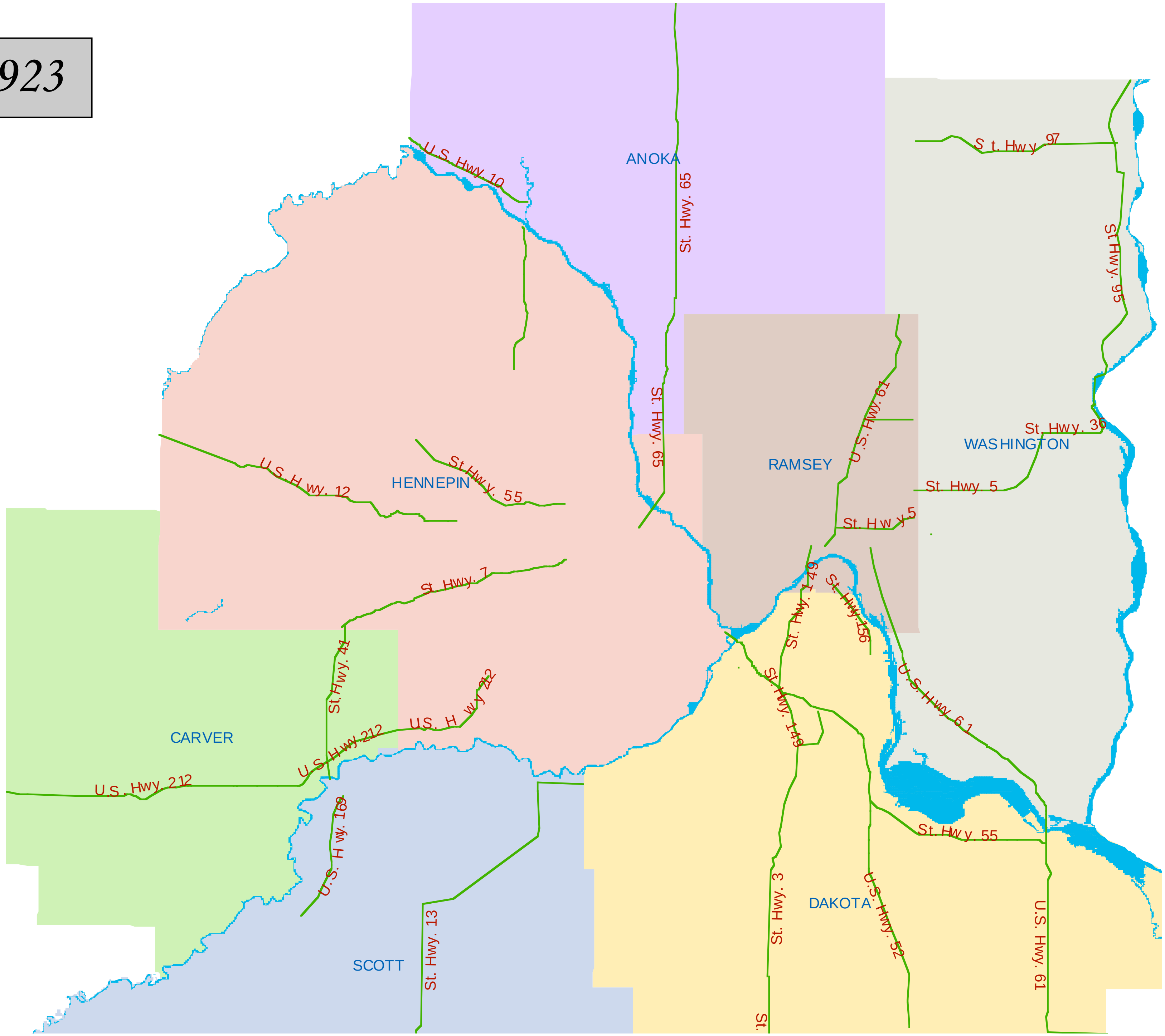
1923



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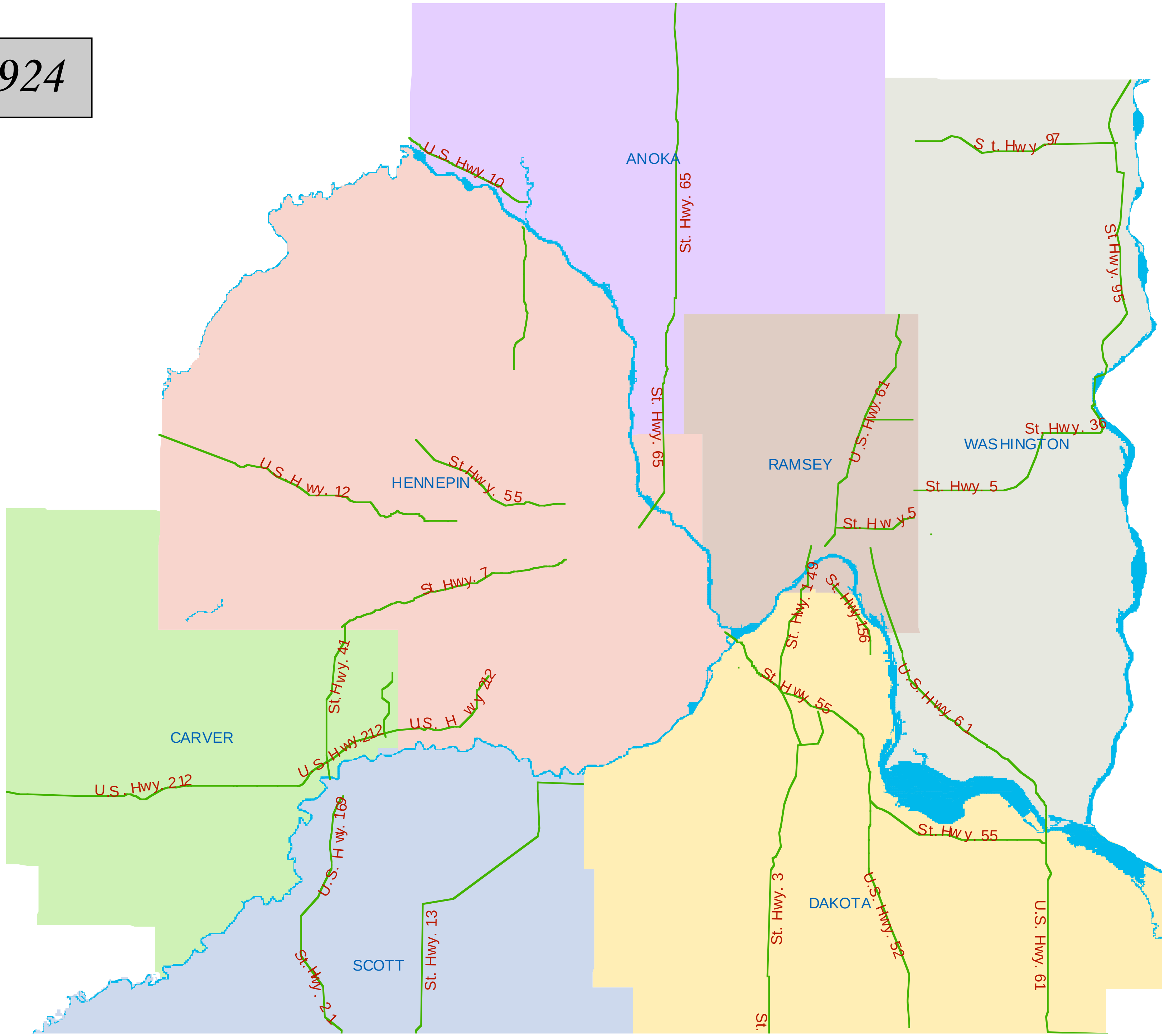
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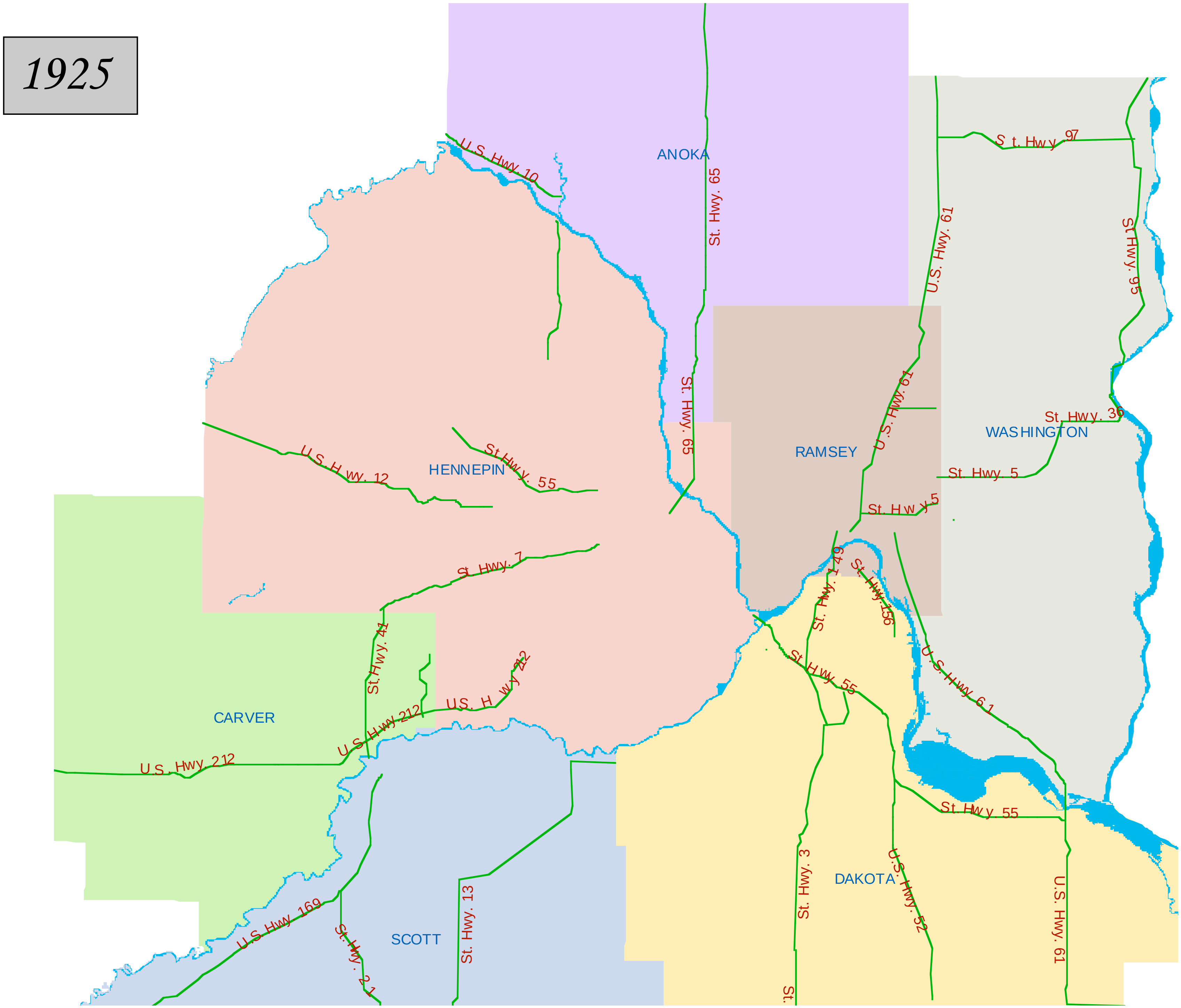
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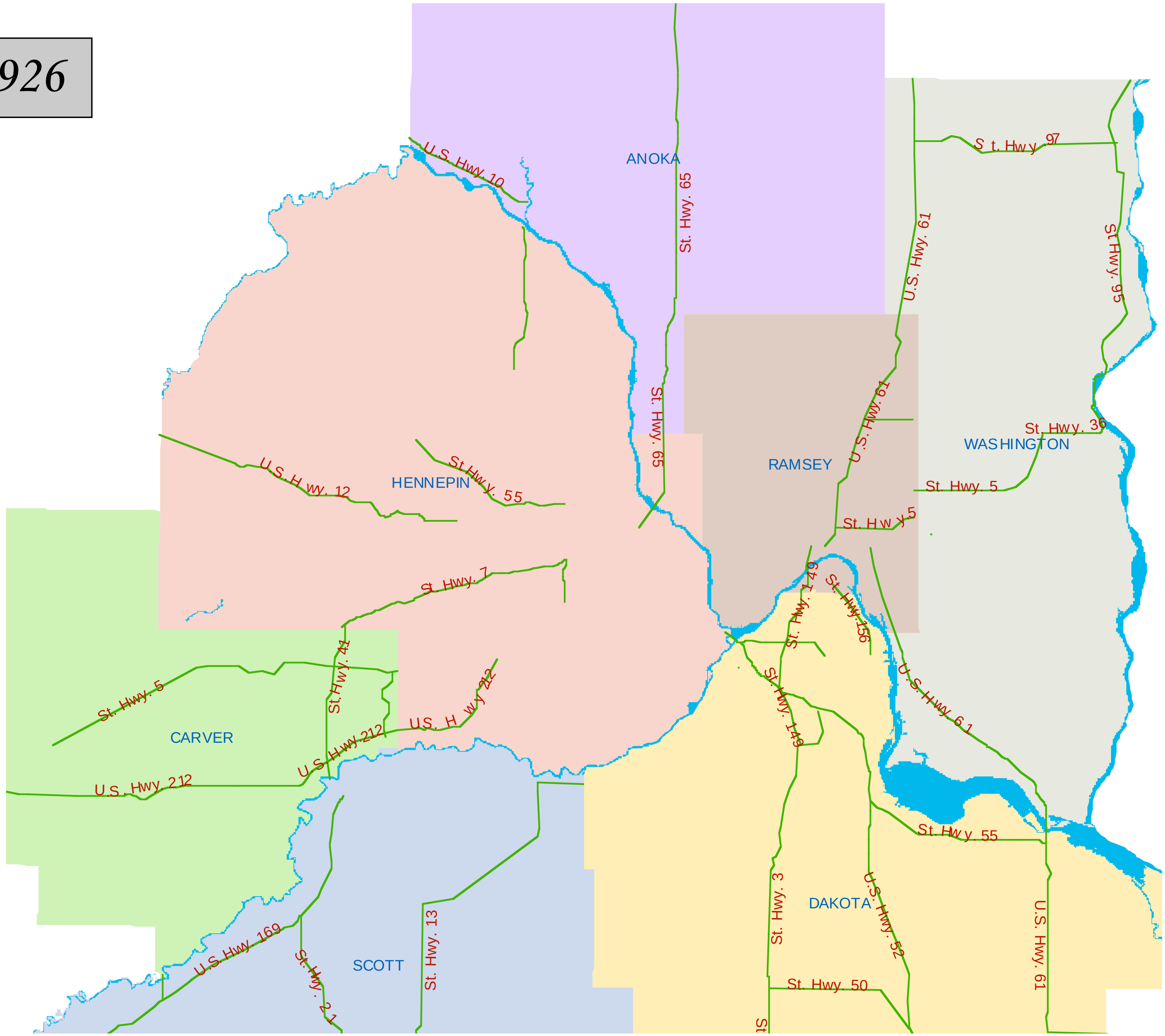
1926



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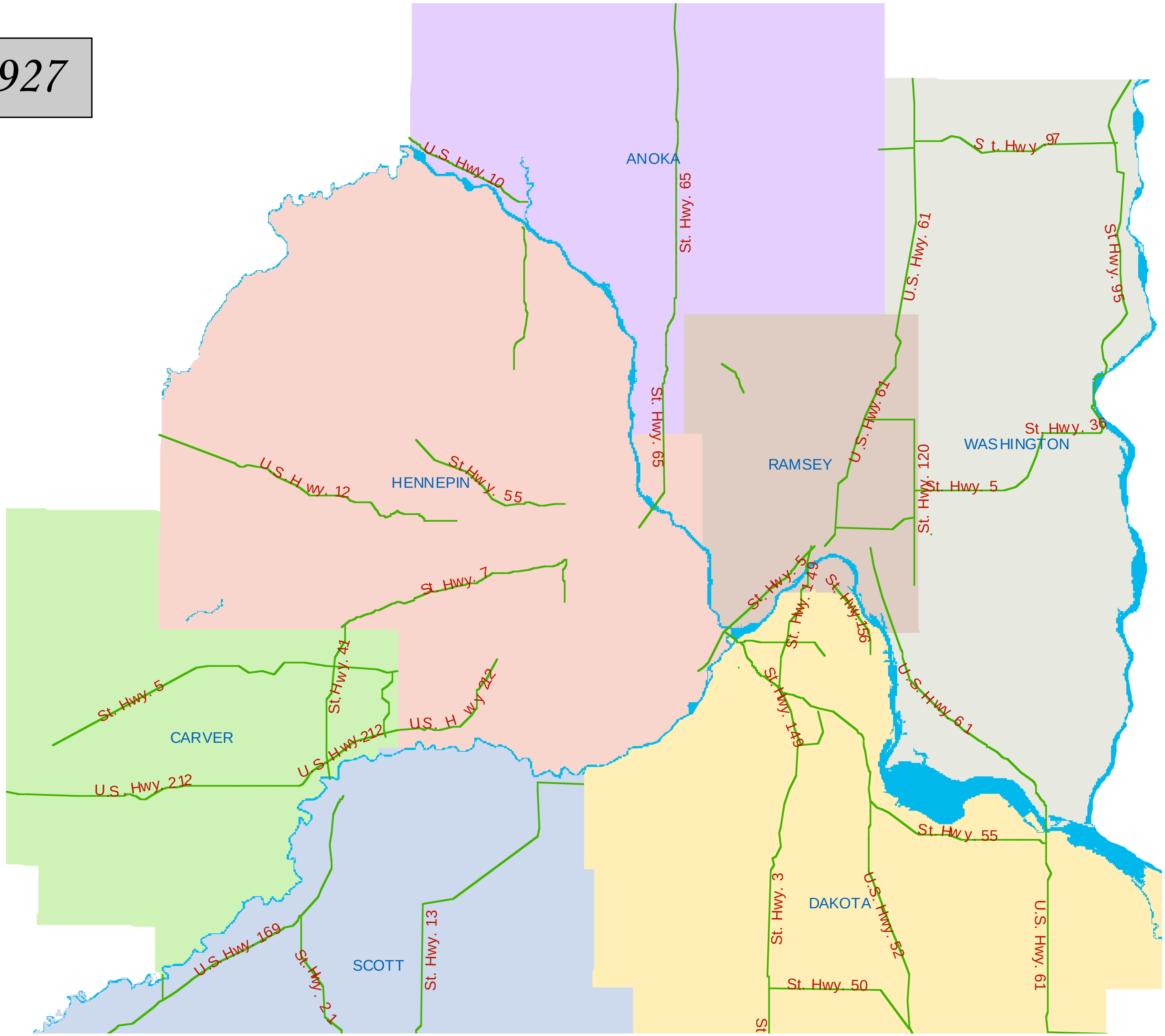
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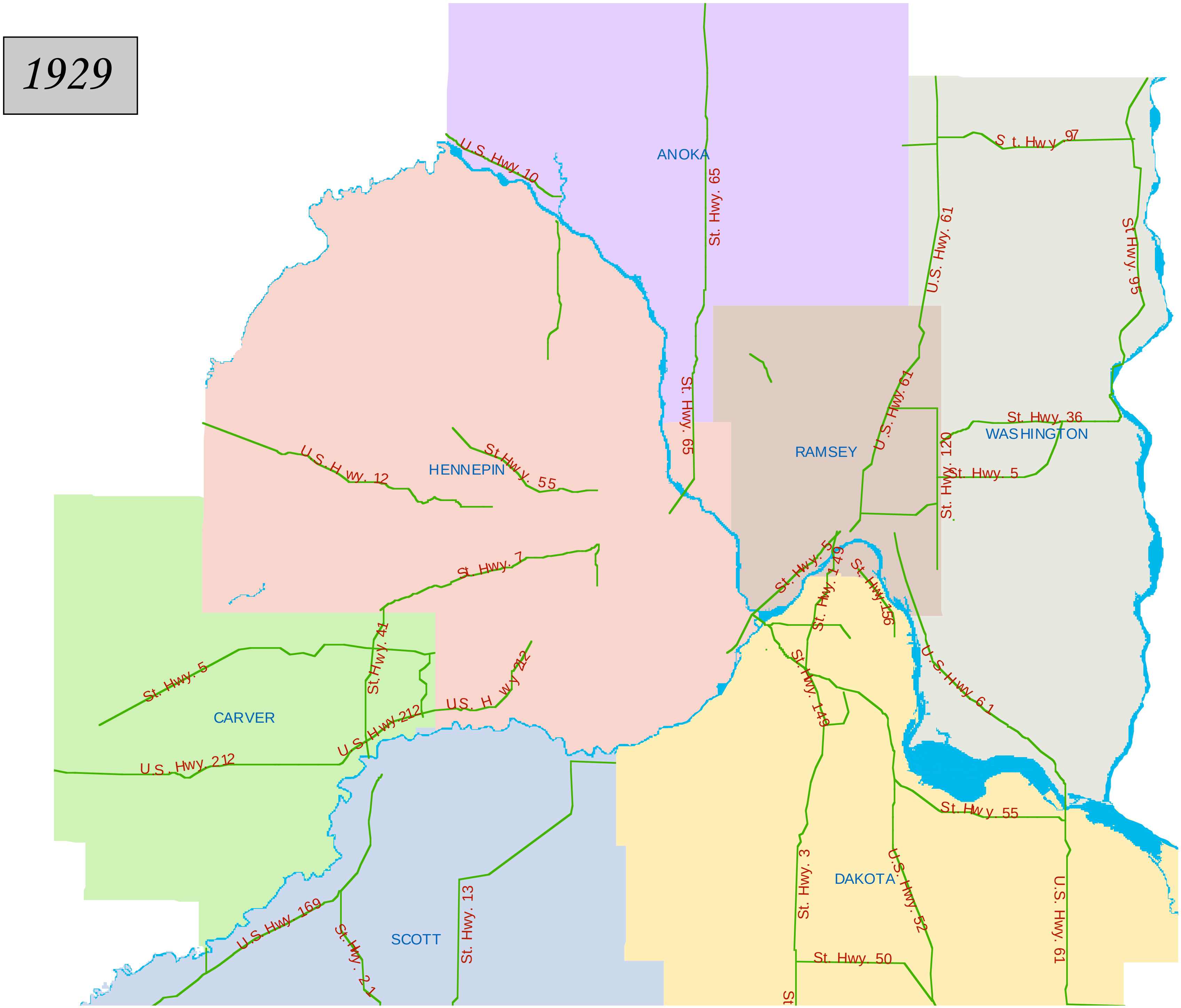
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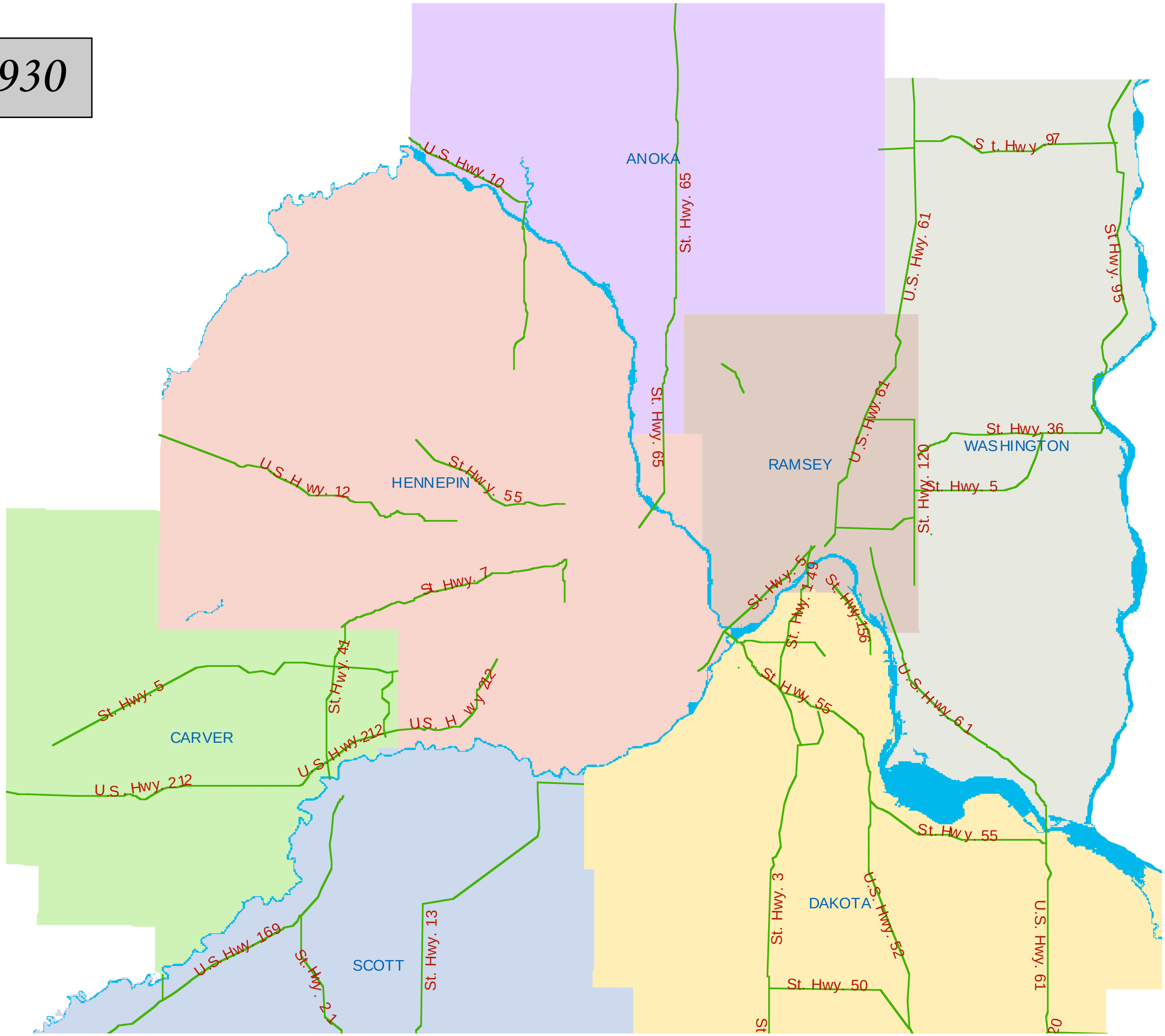
1930



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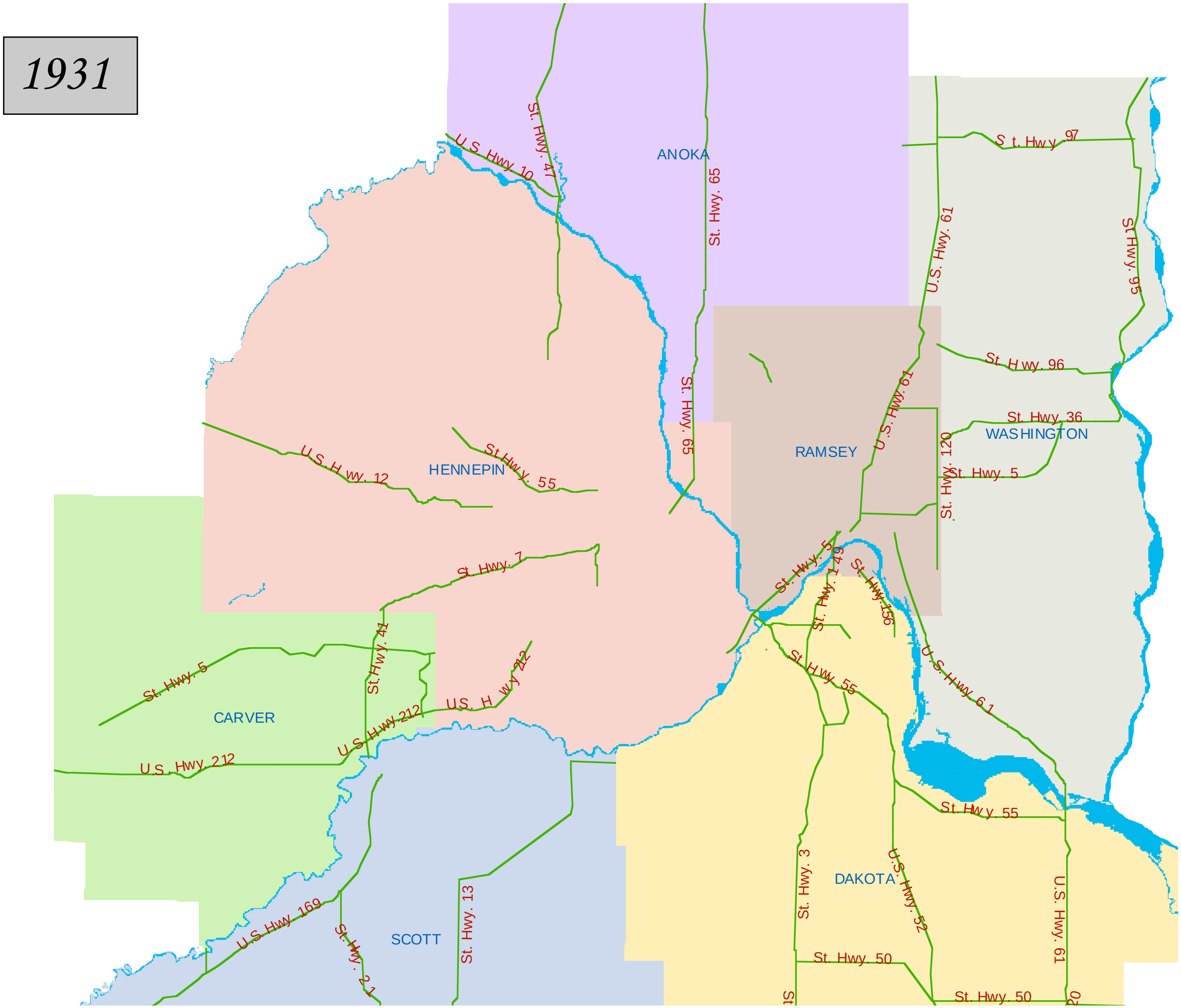

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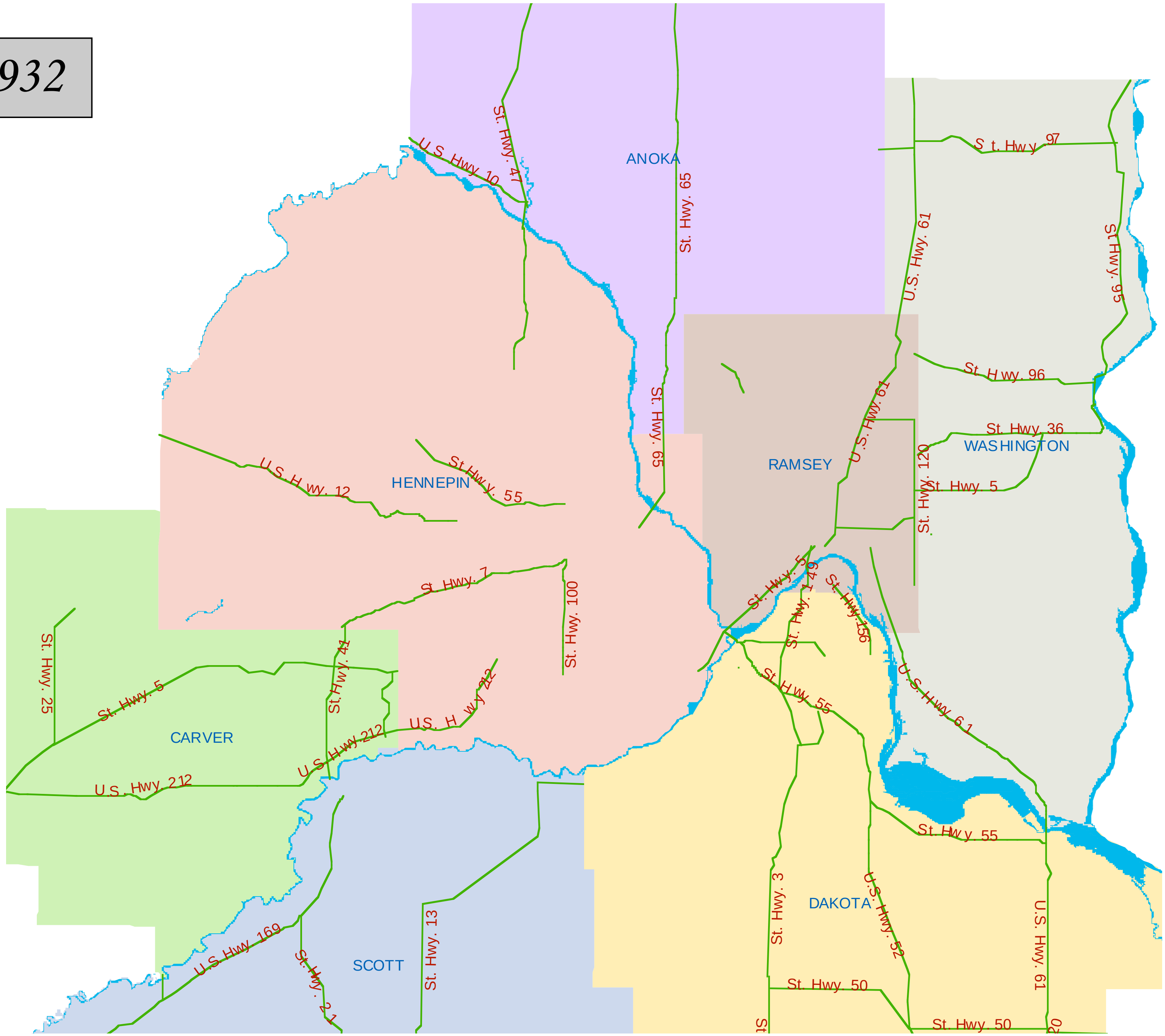
1932



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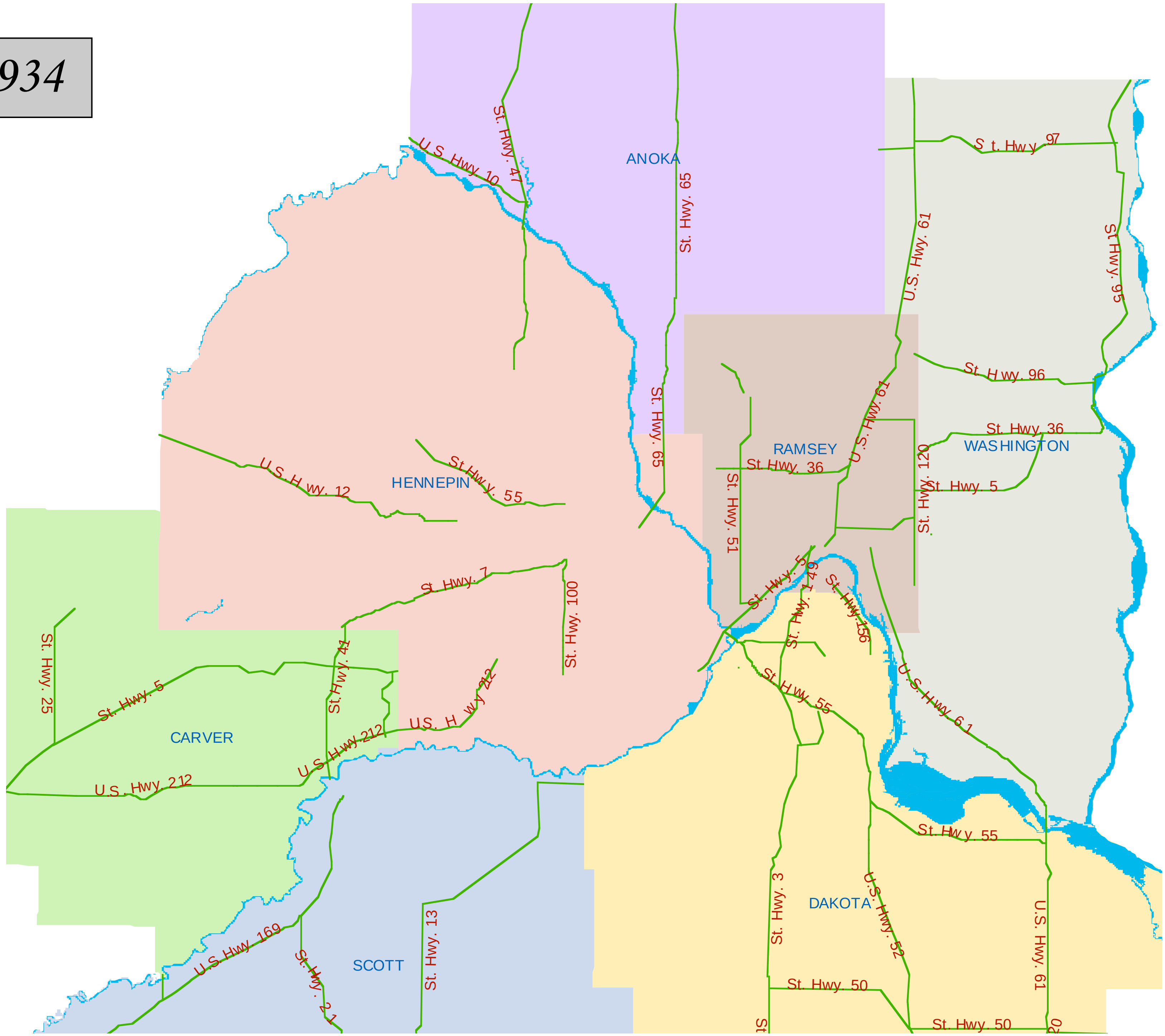
1934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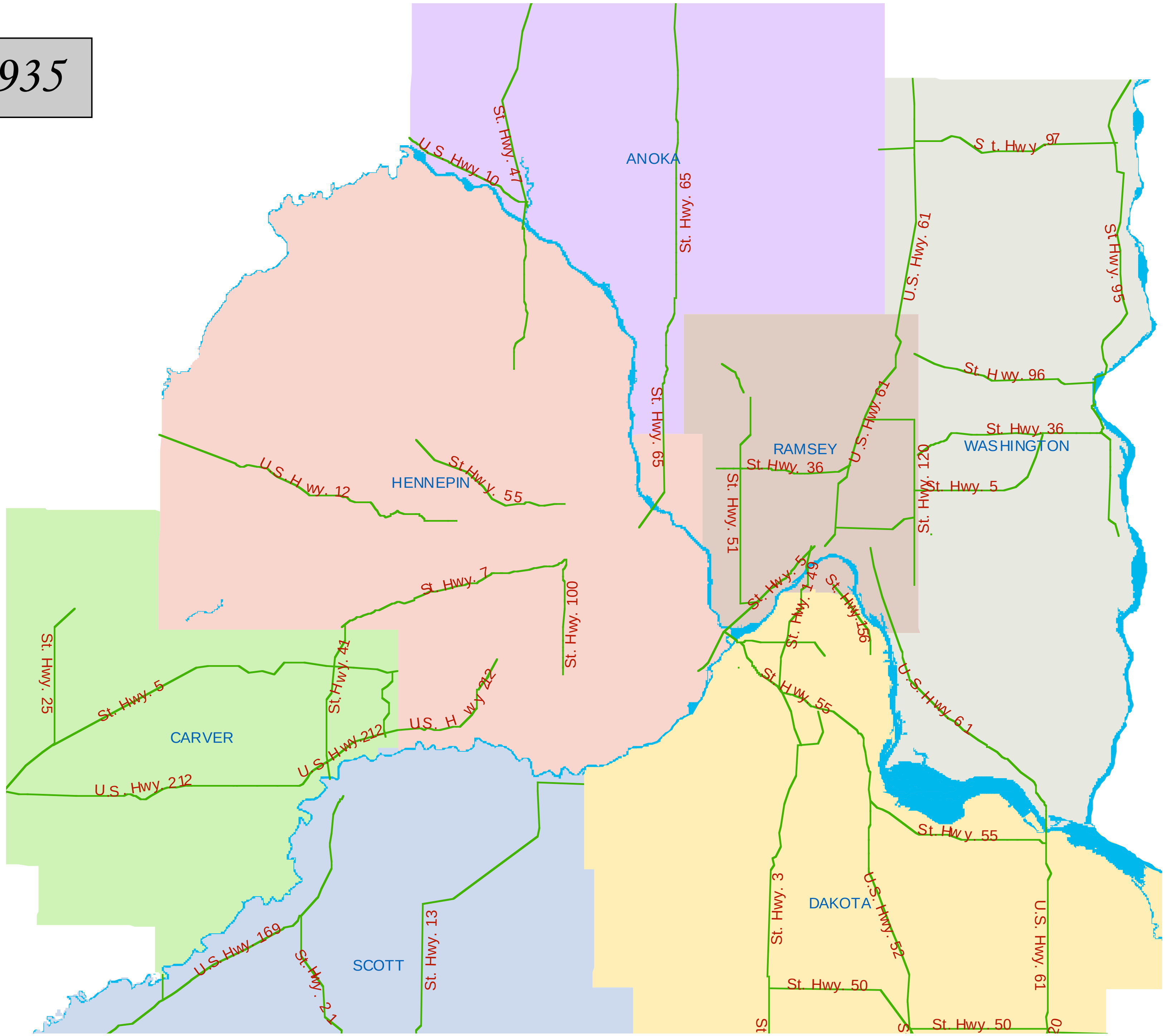
1935



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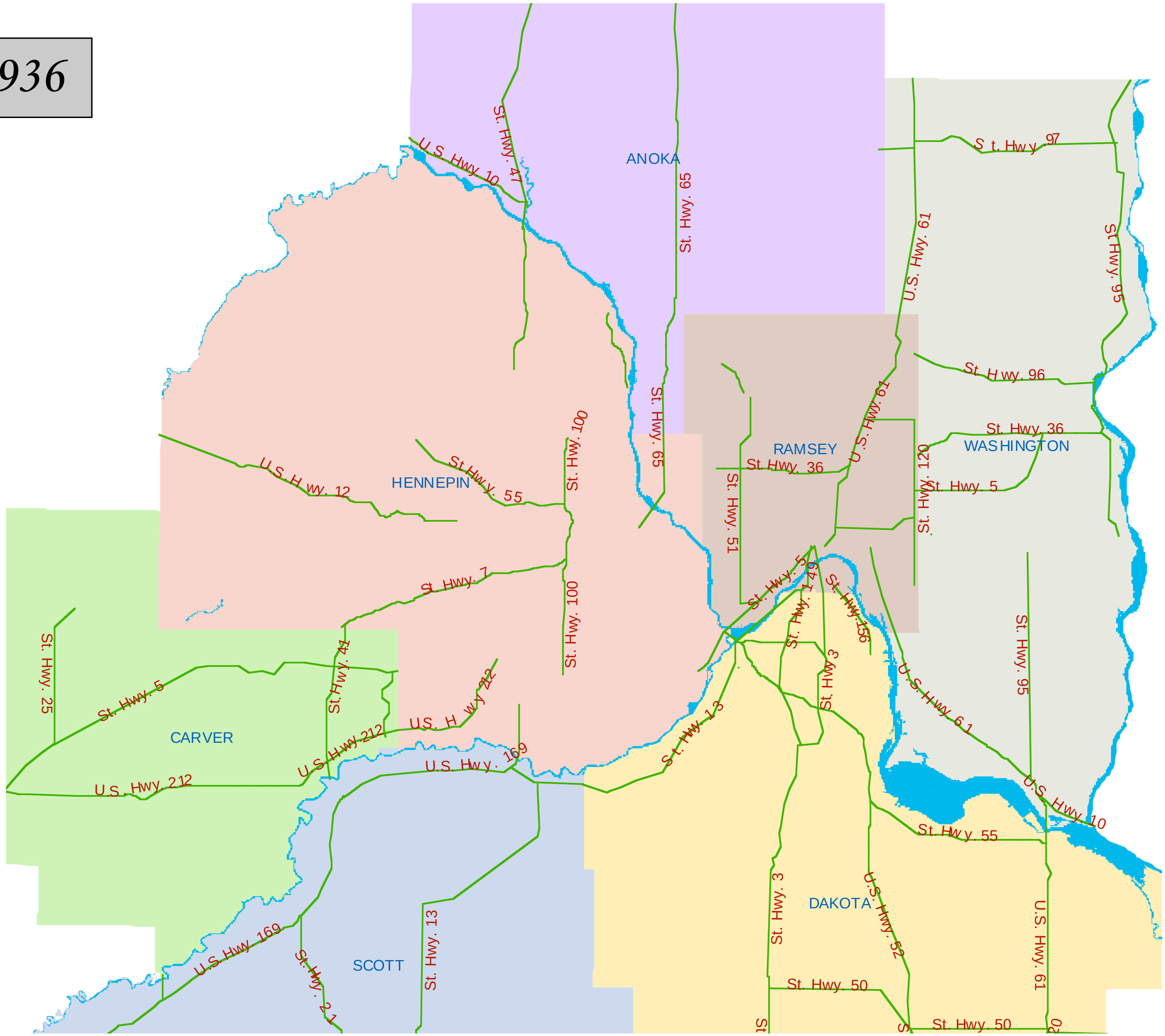
1936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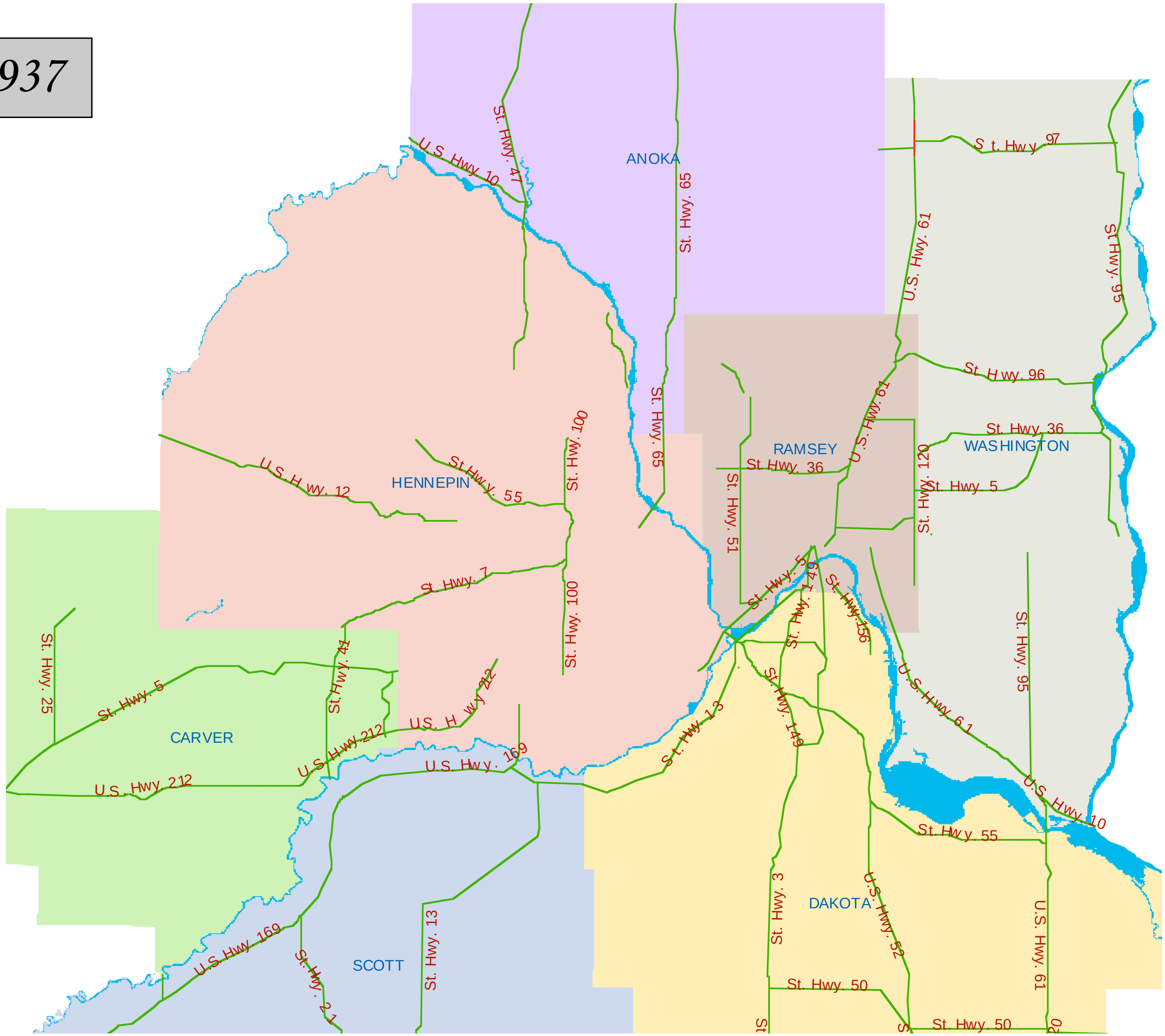
1937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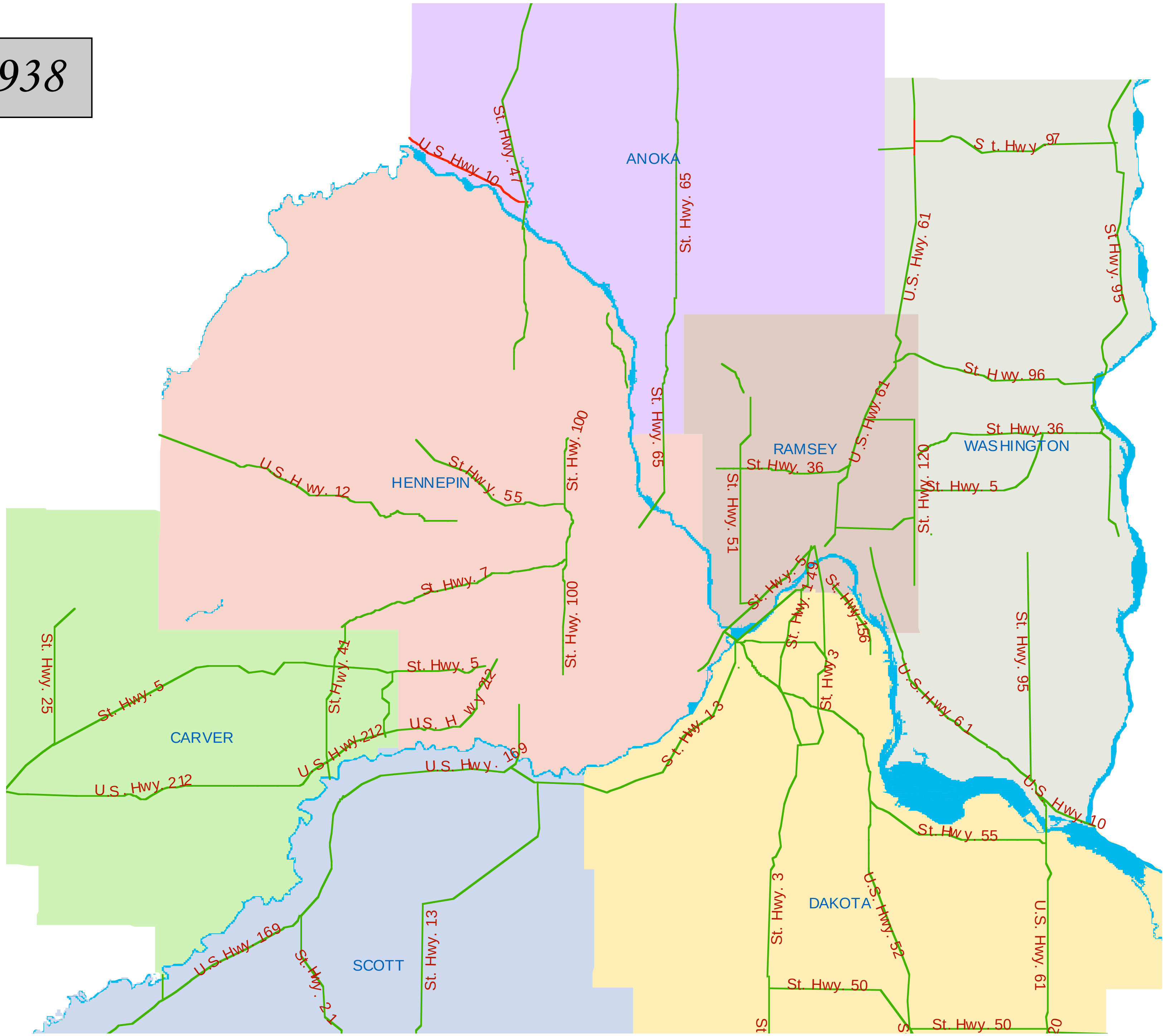
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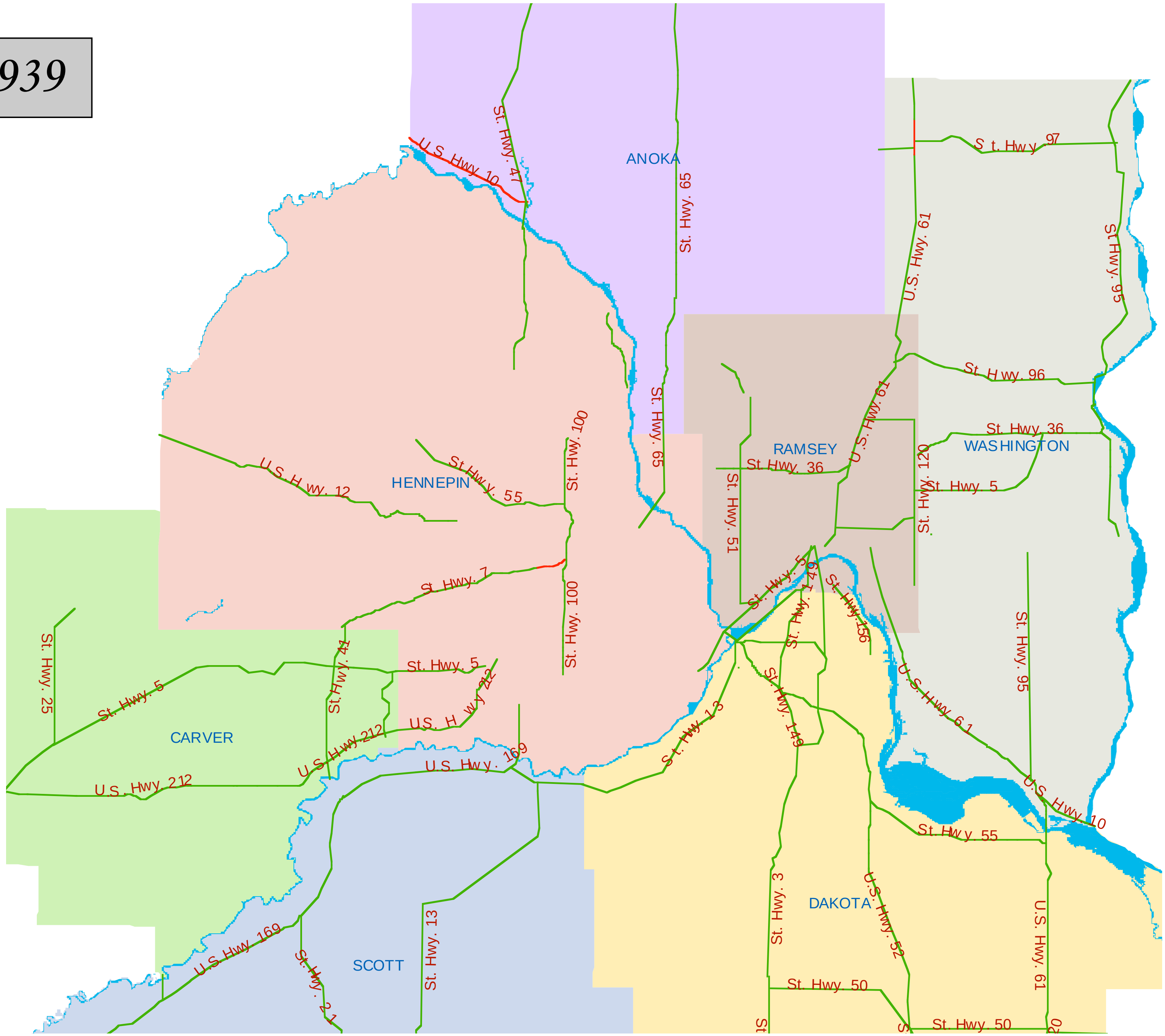
1939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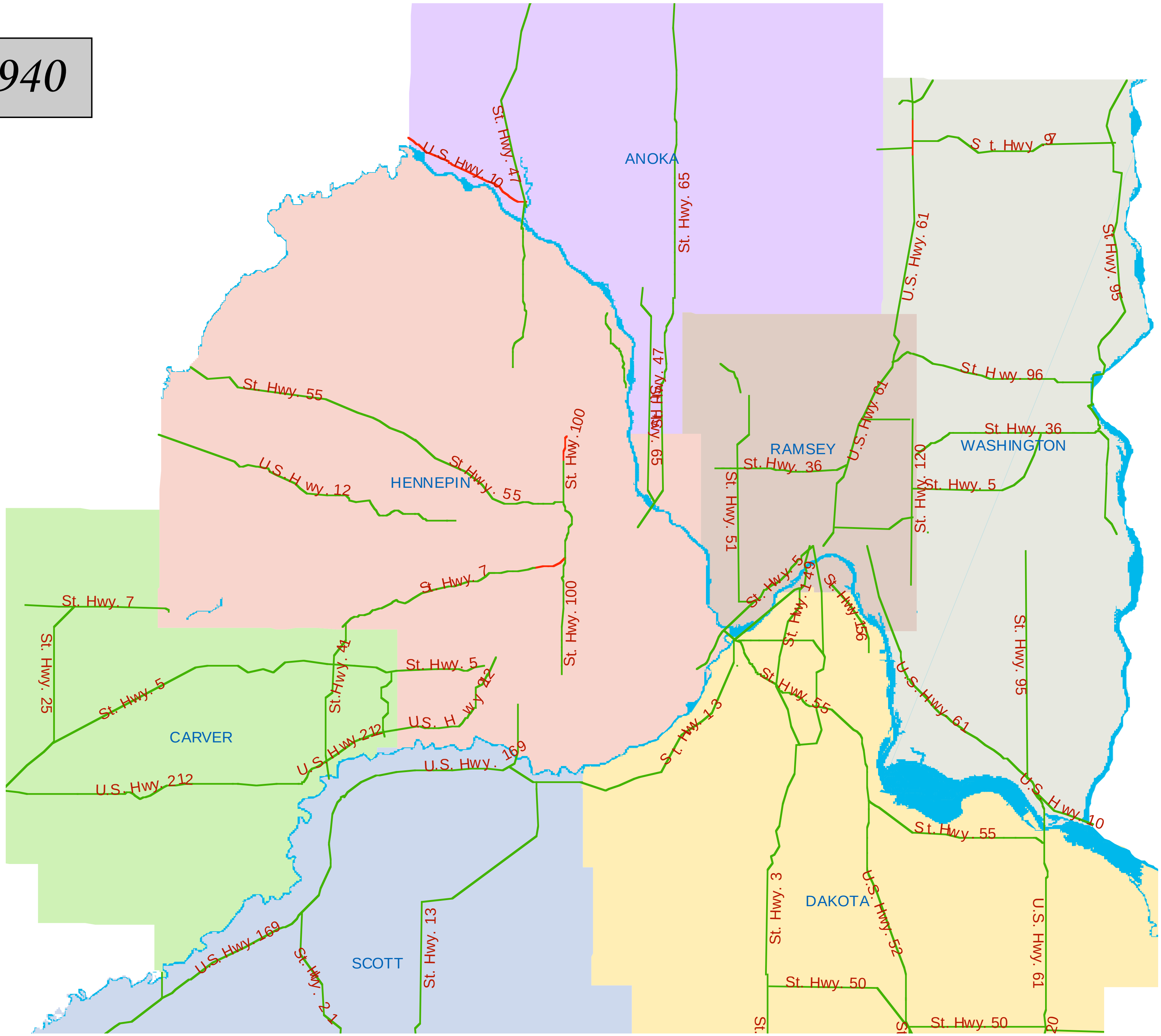
1940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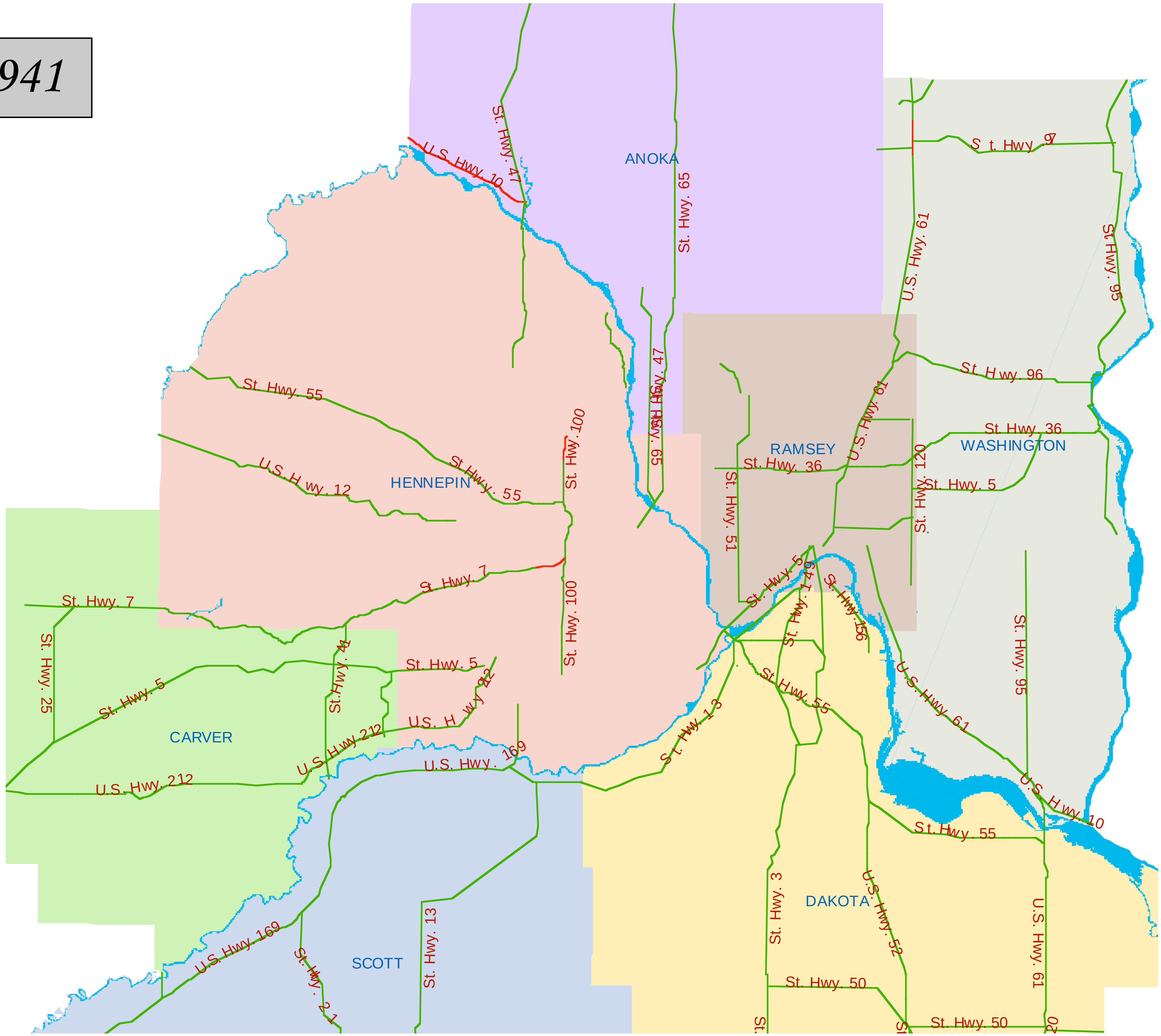
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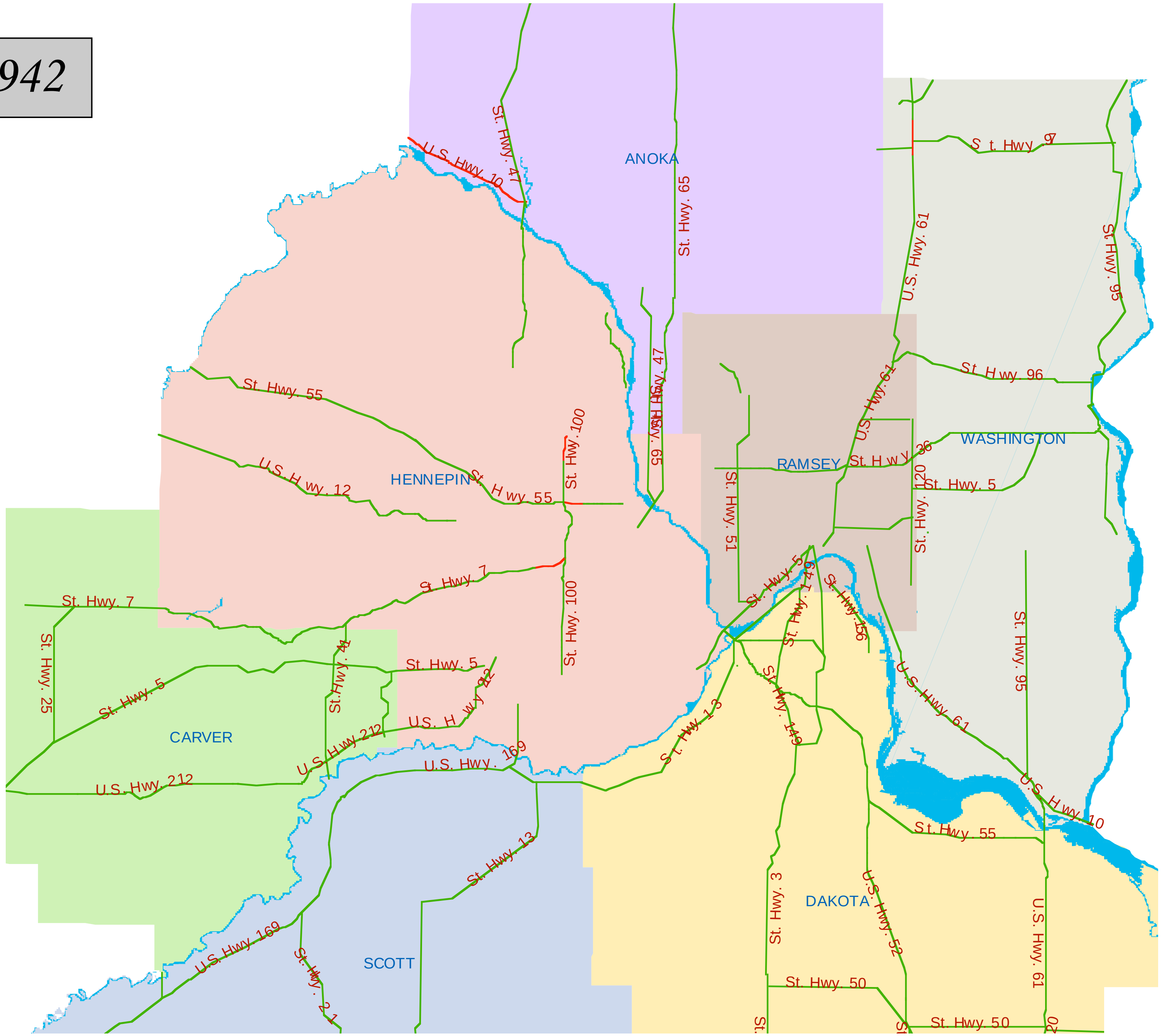

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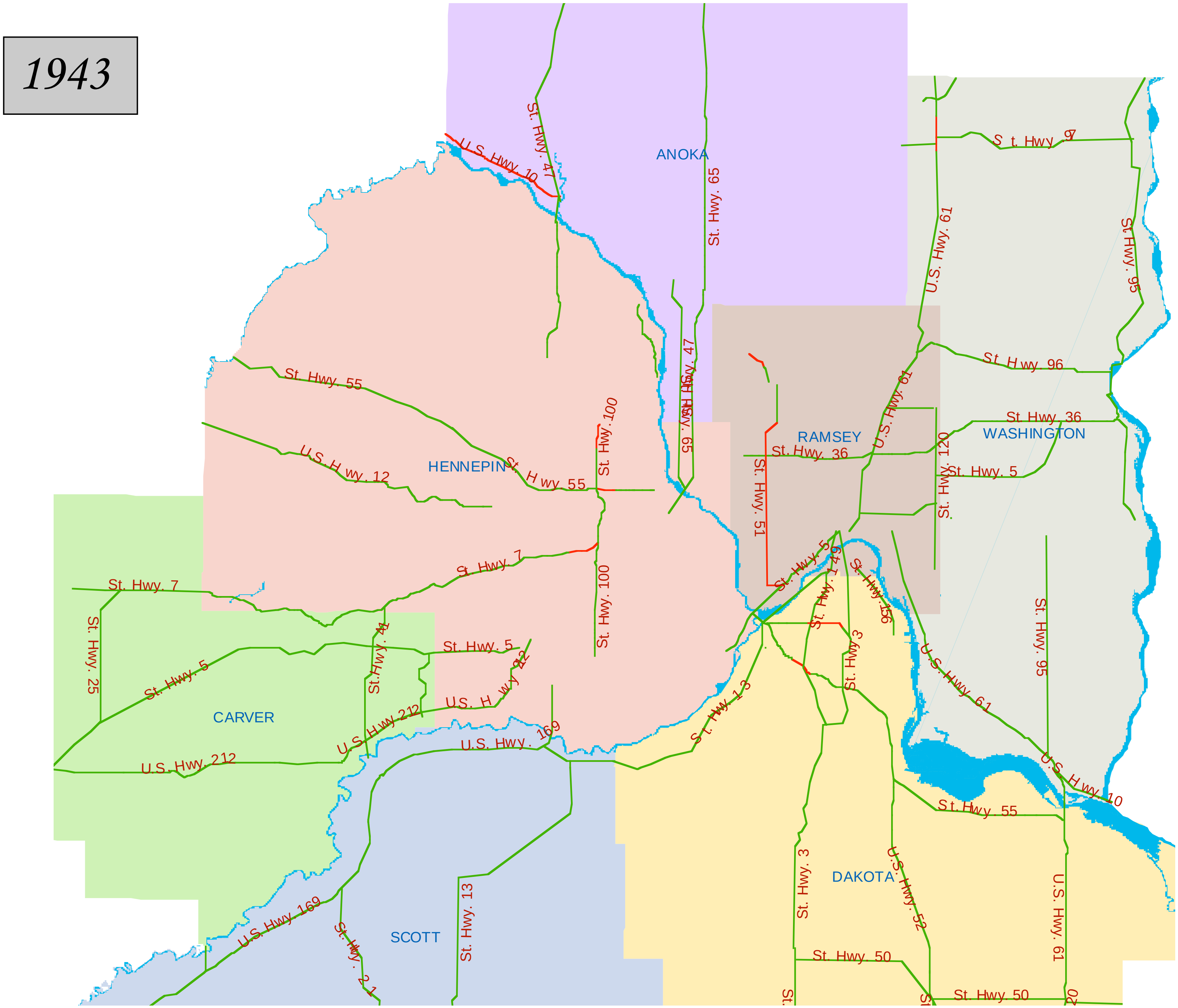
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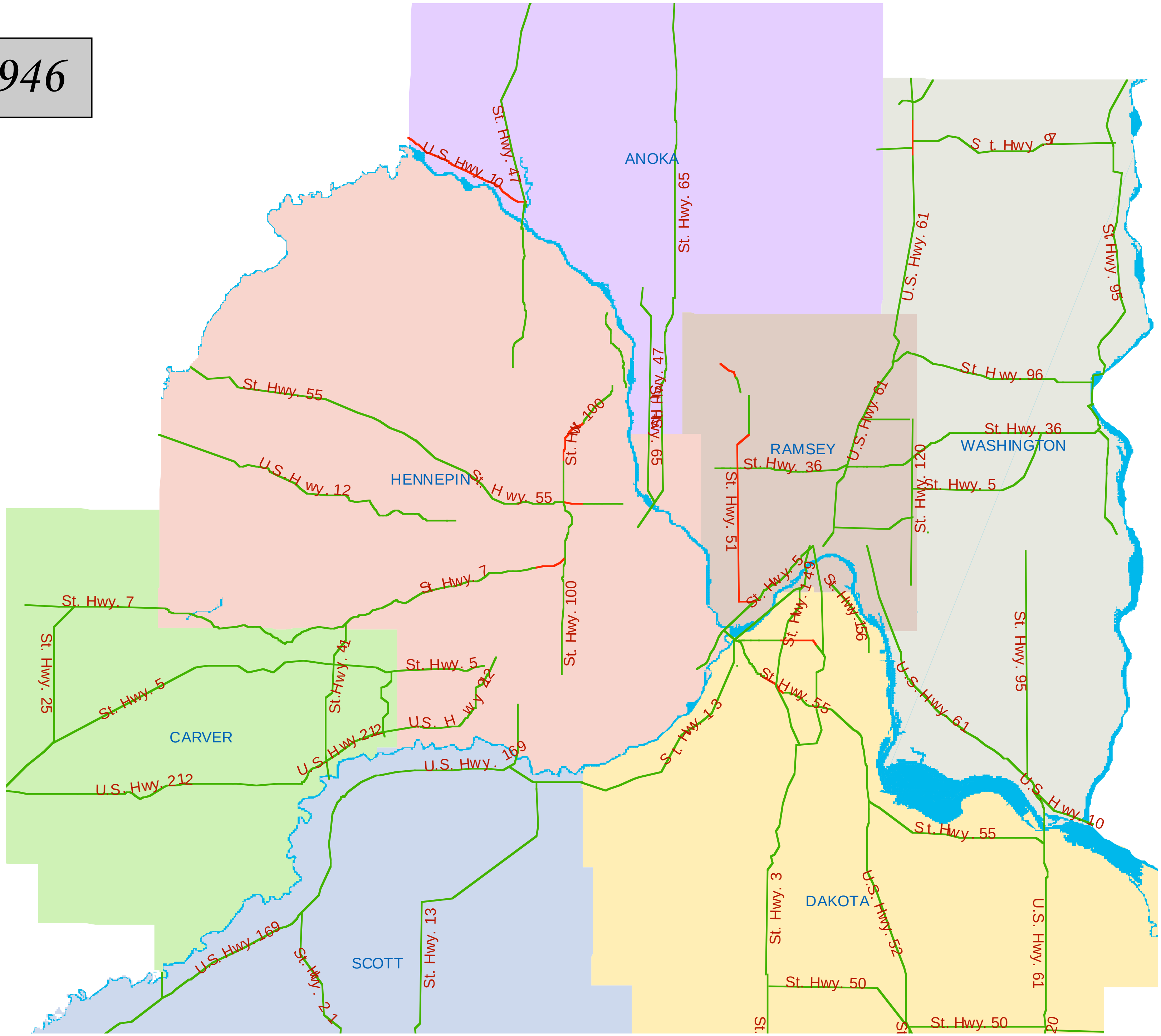
1946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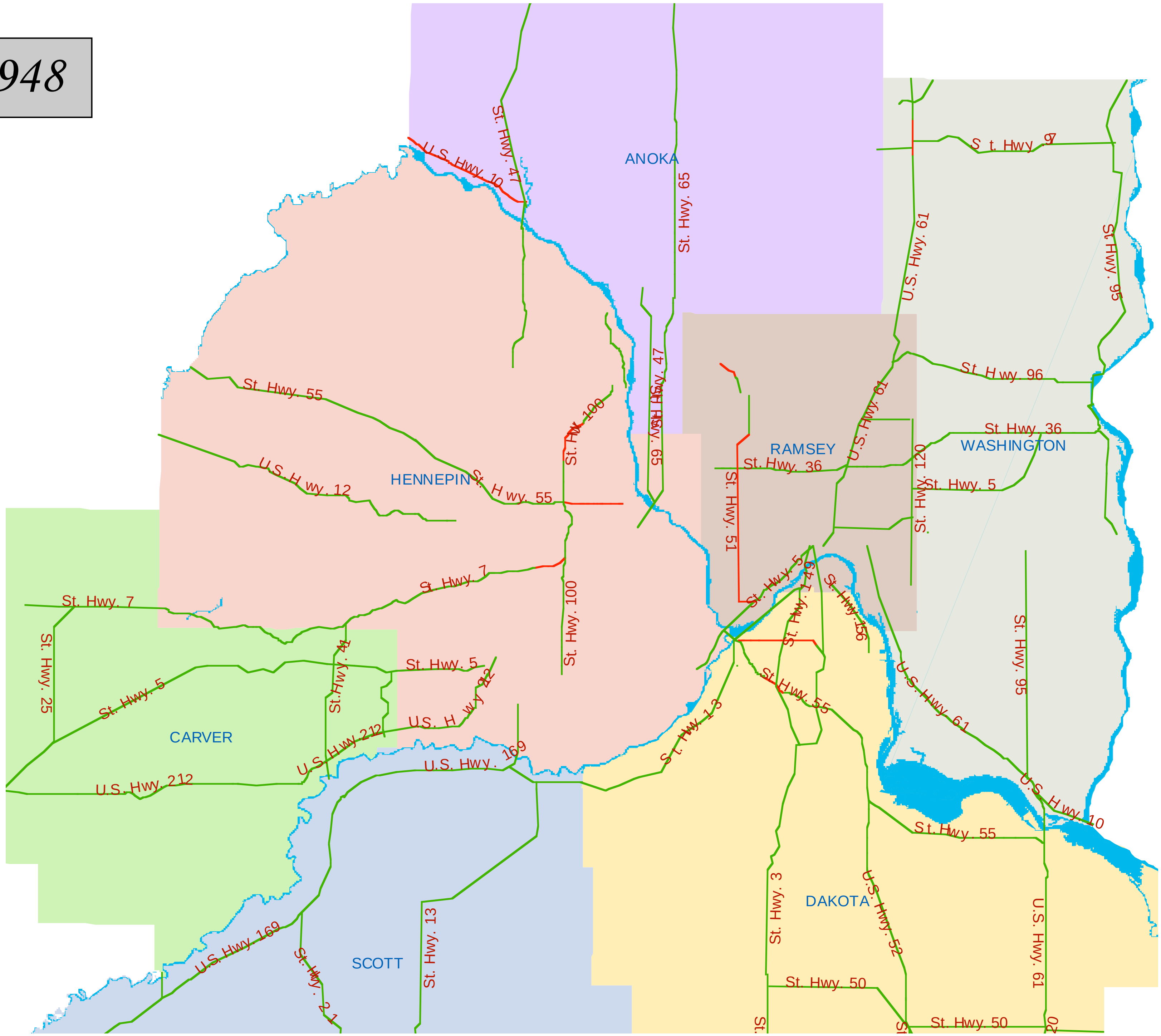
1948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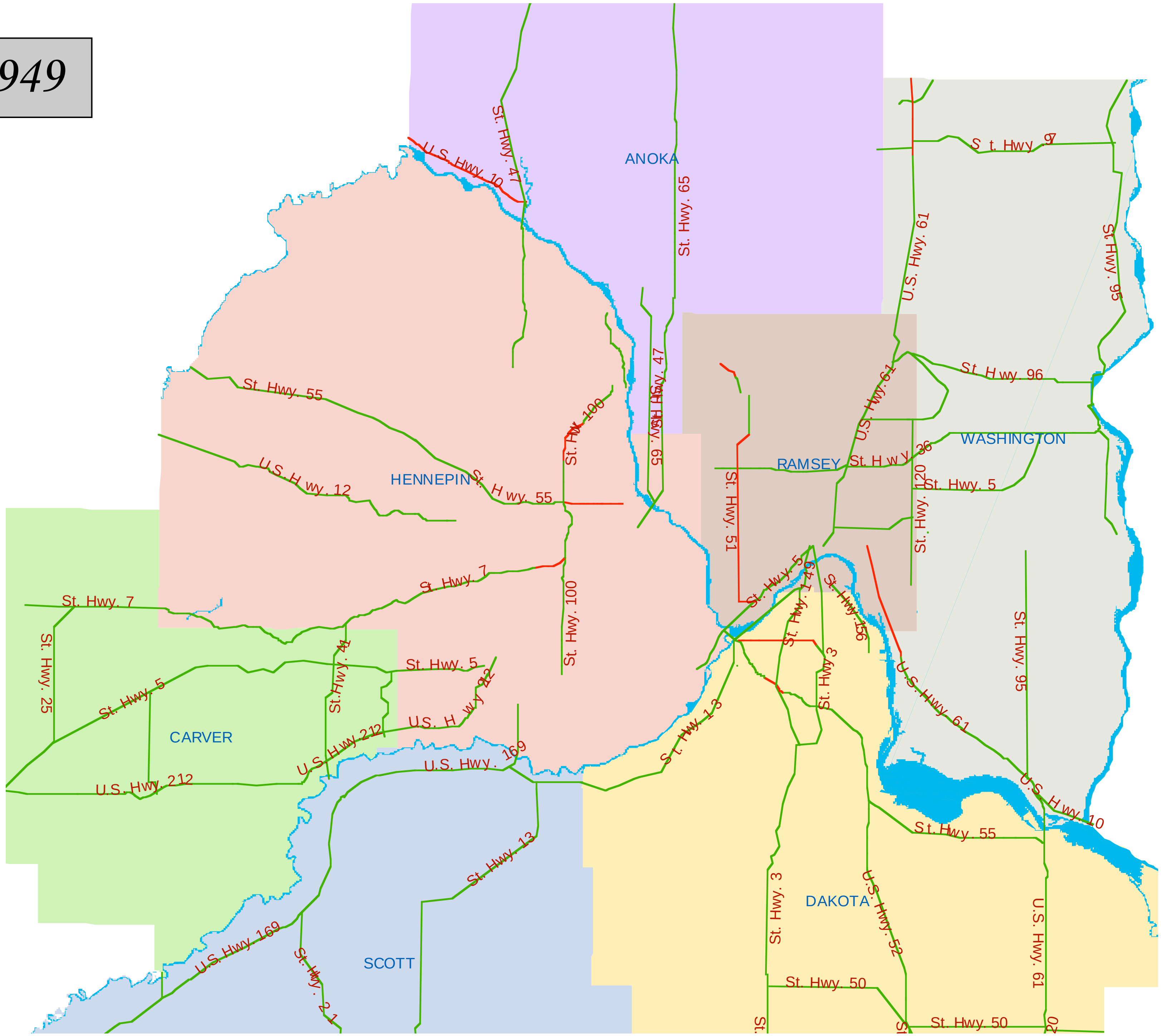
1949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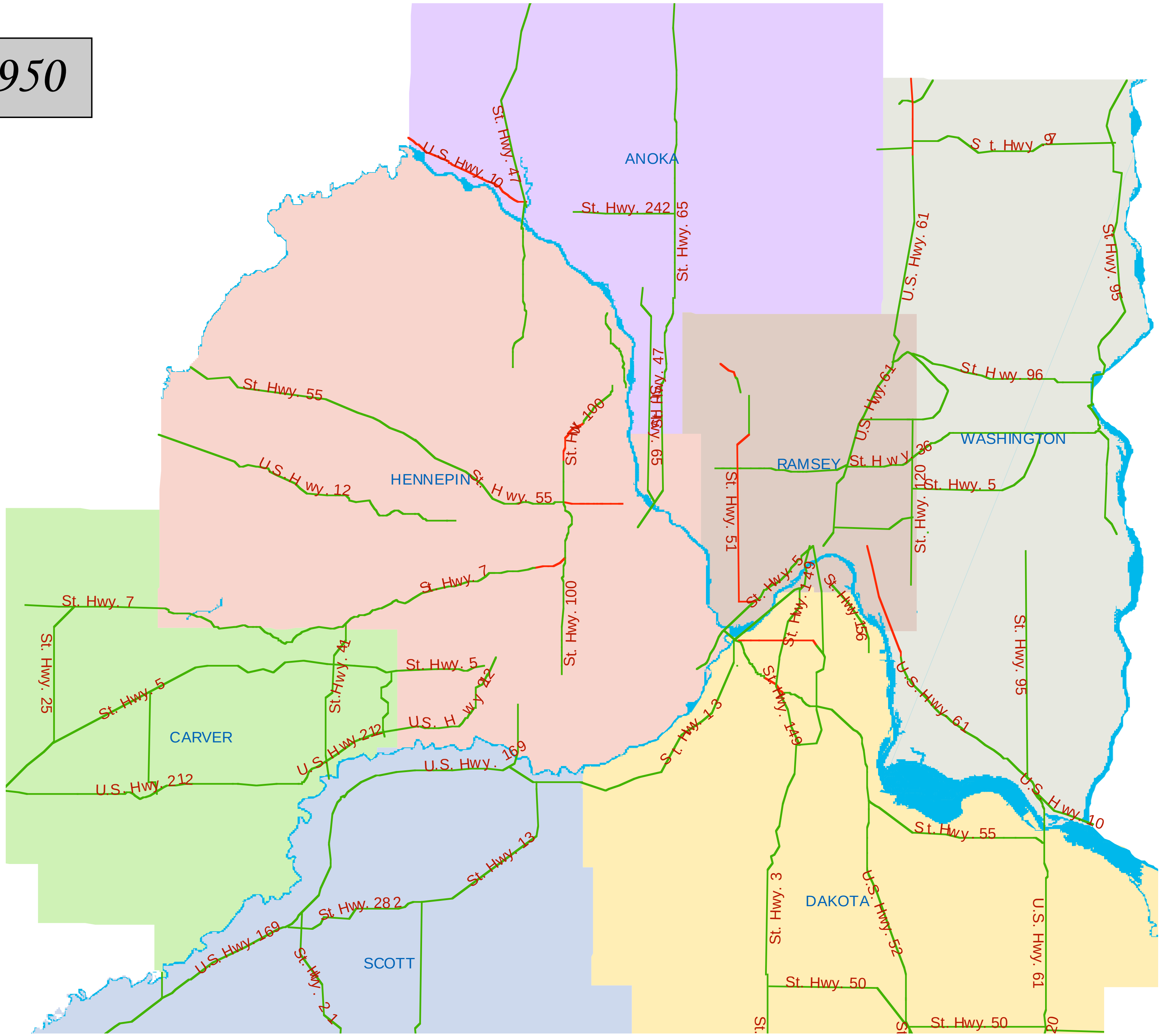
1950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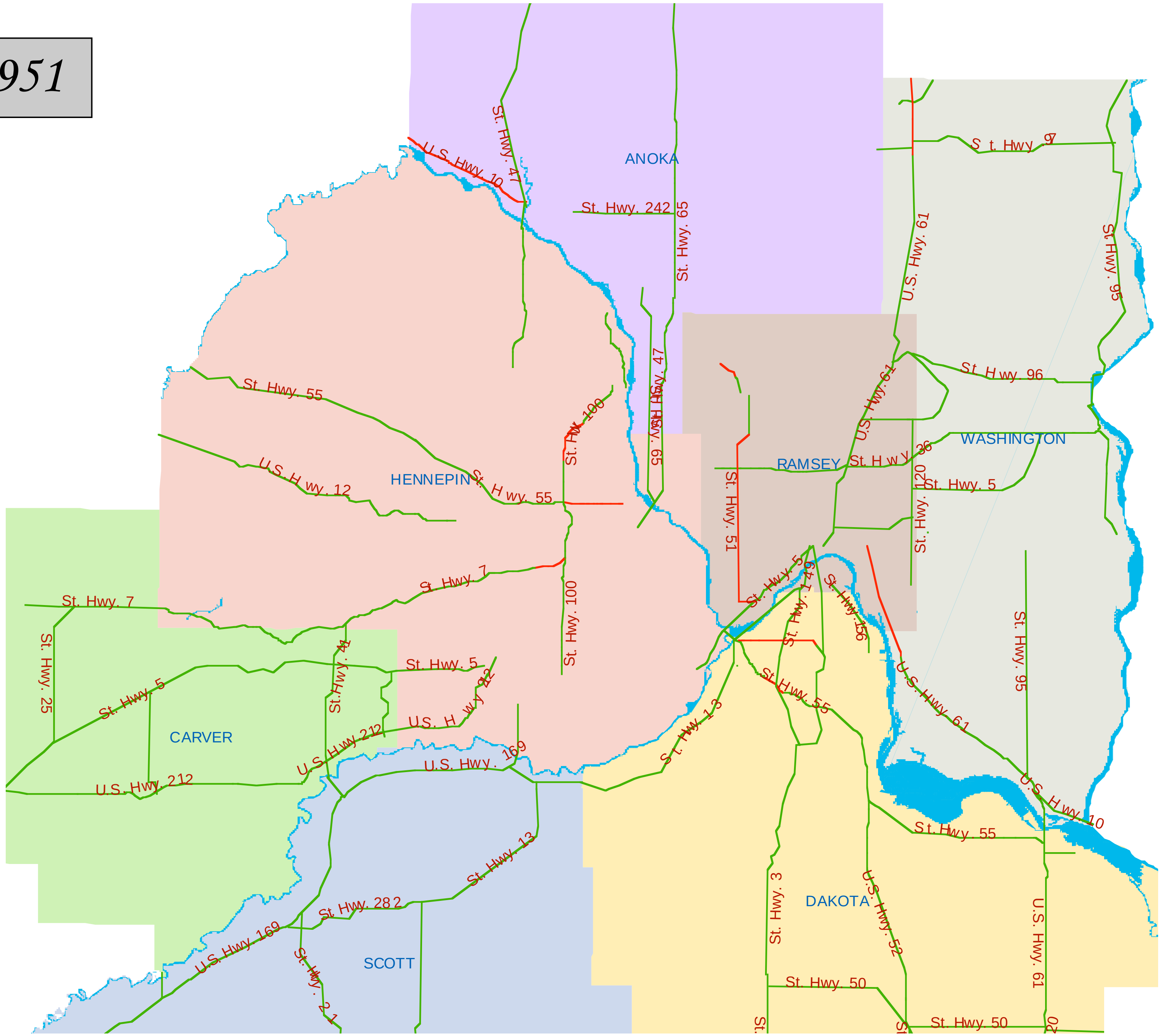
1951



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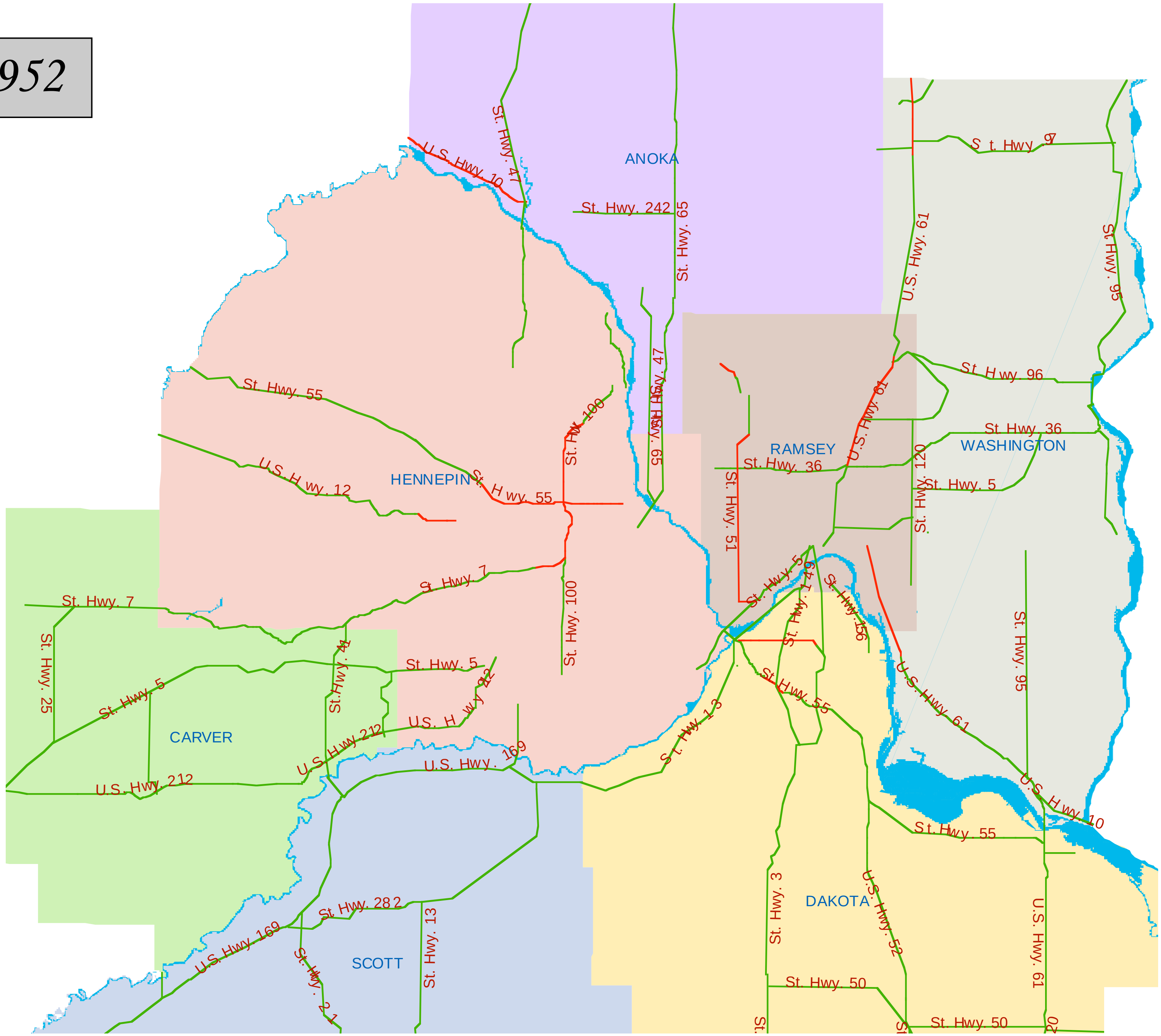
1952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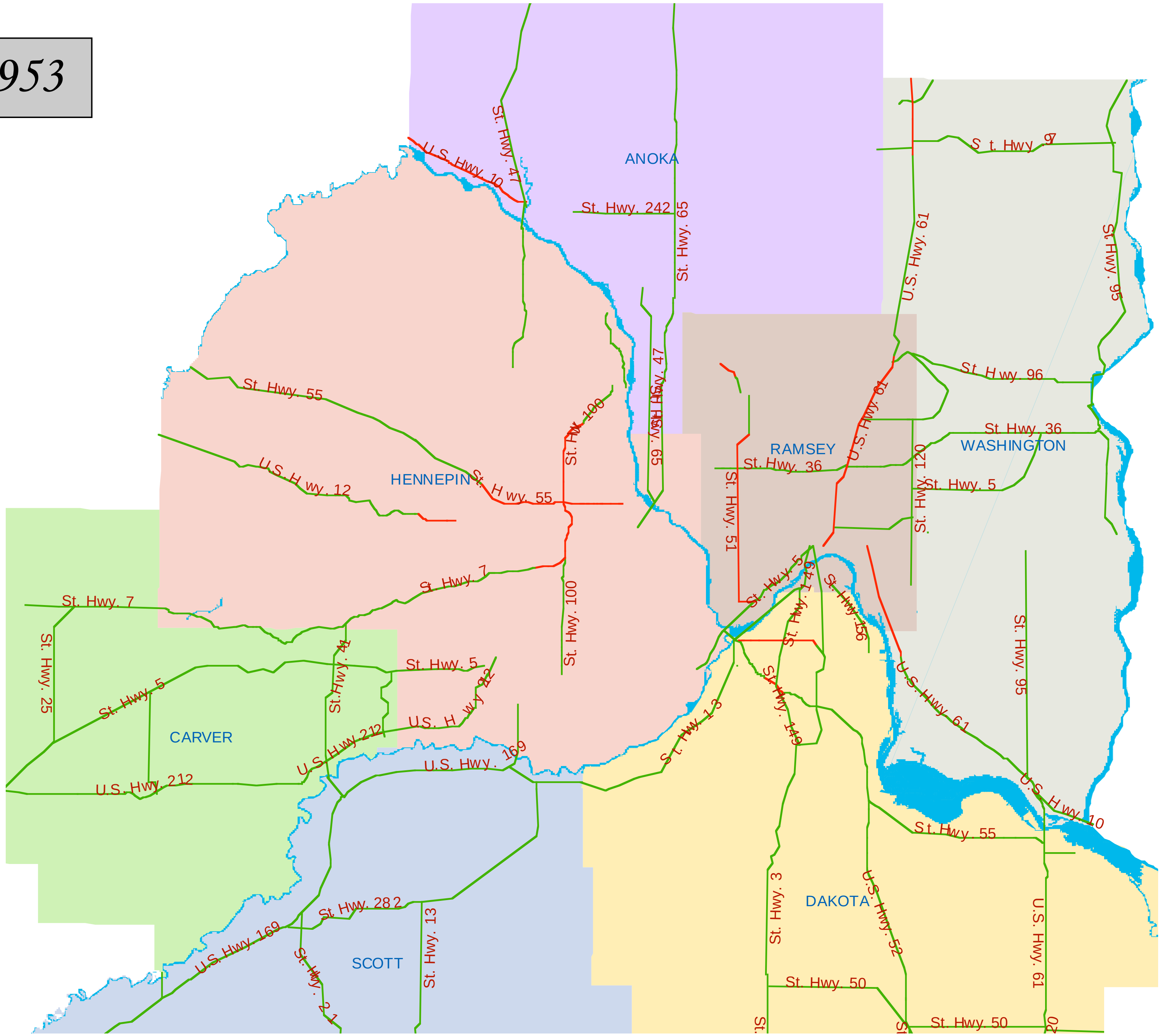
1953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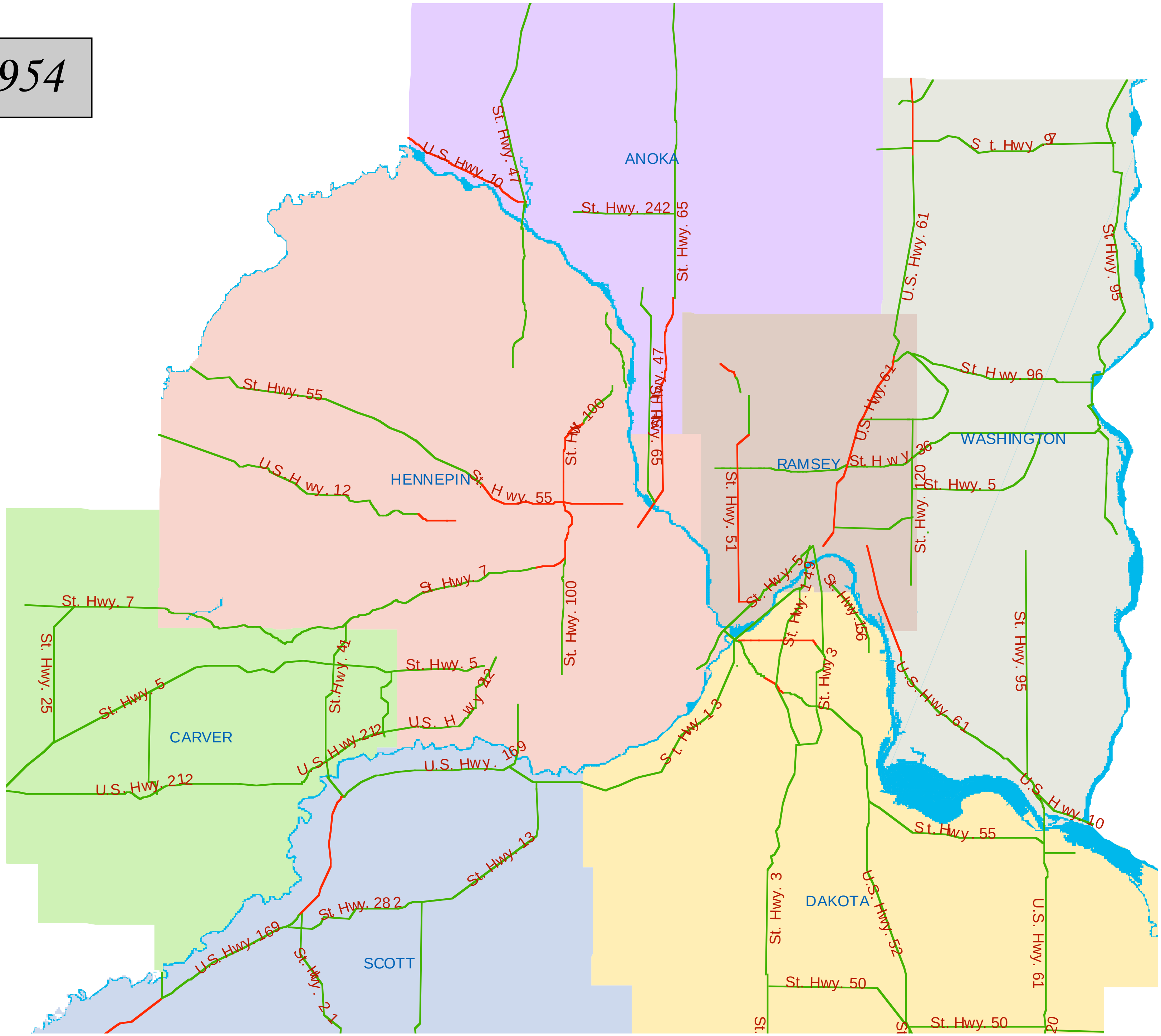
1954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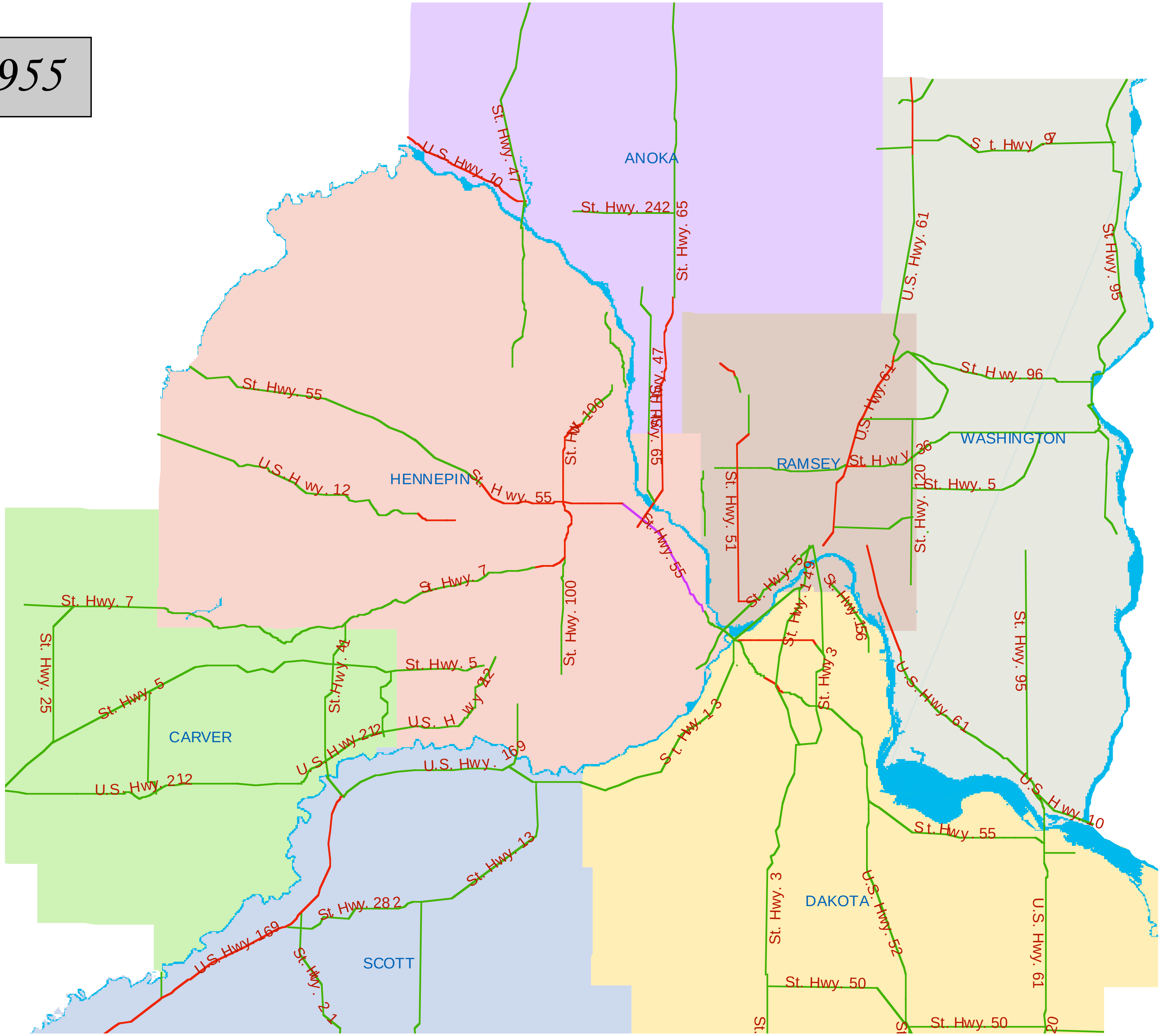
1955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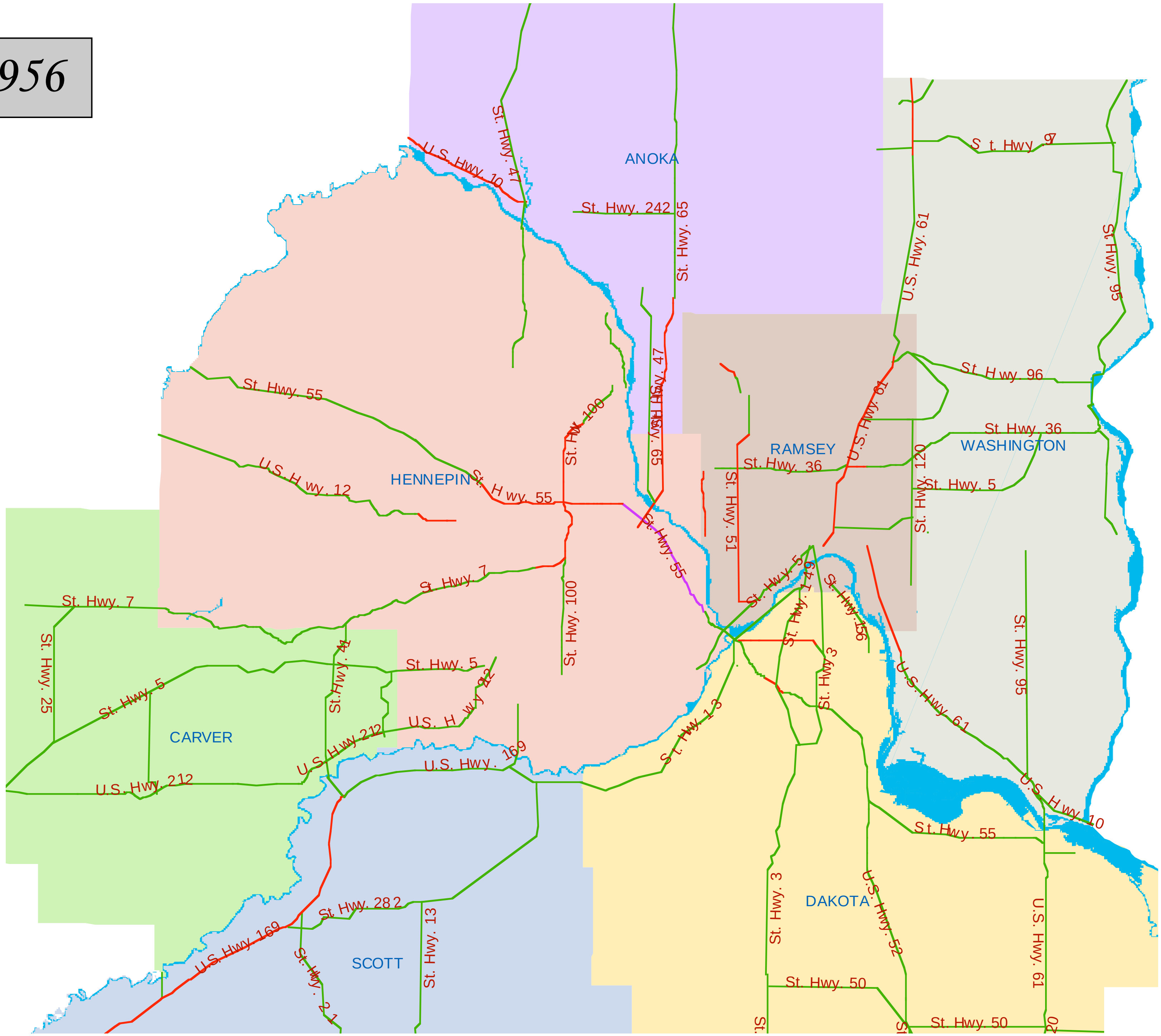
1956



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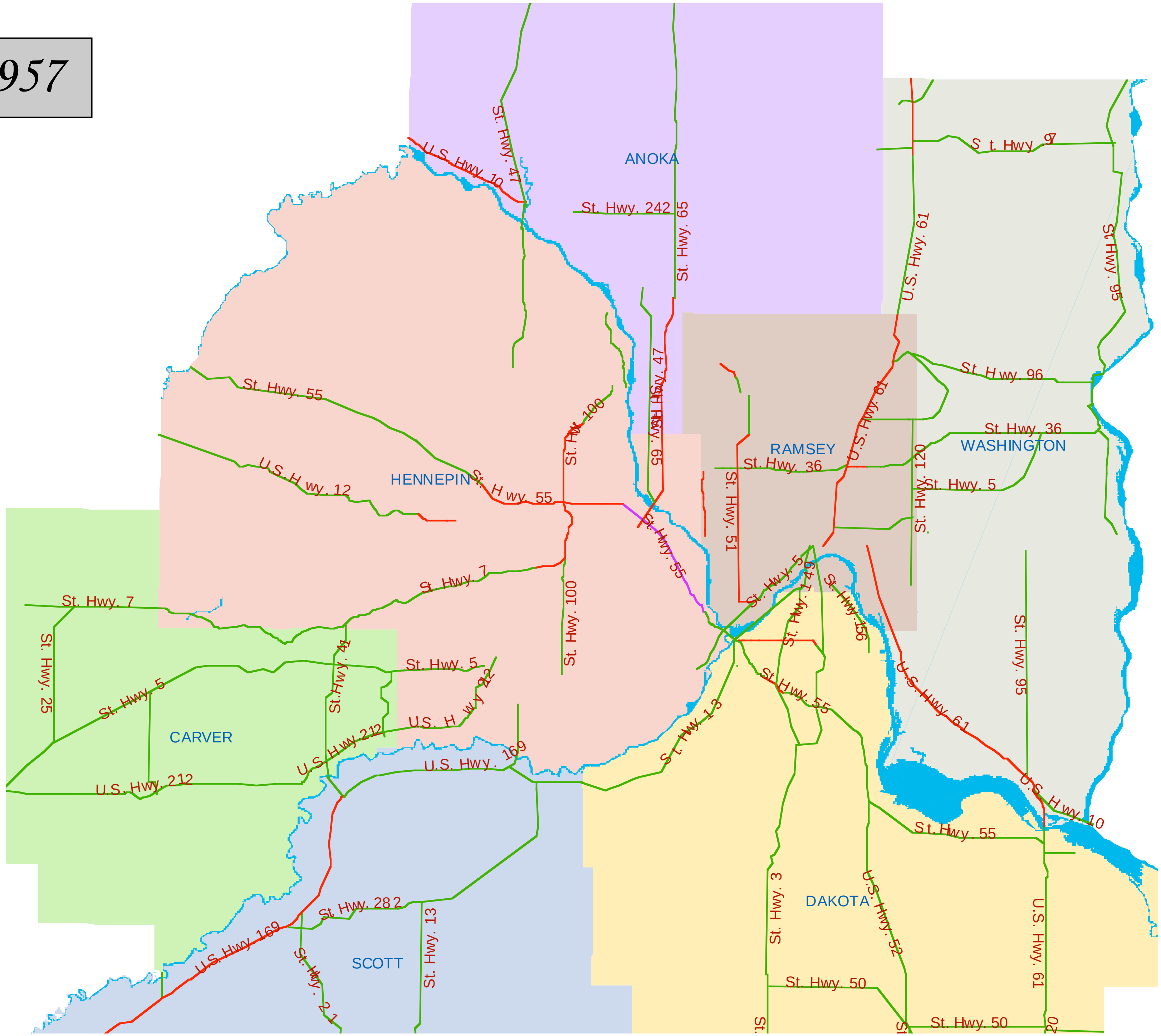
1957



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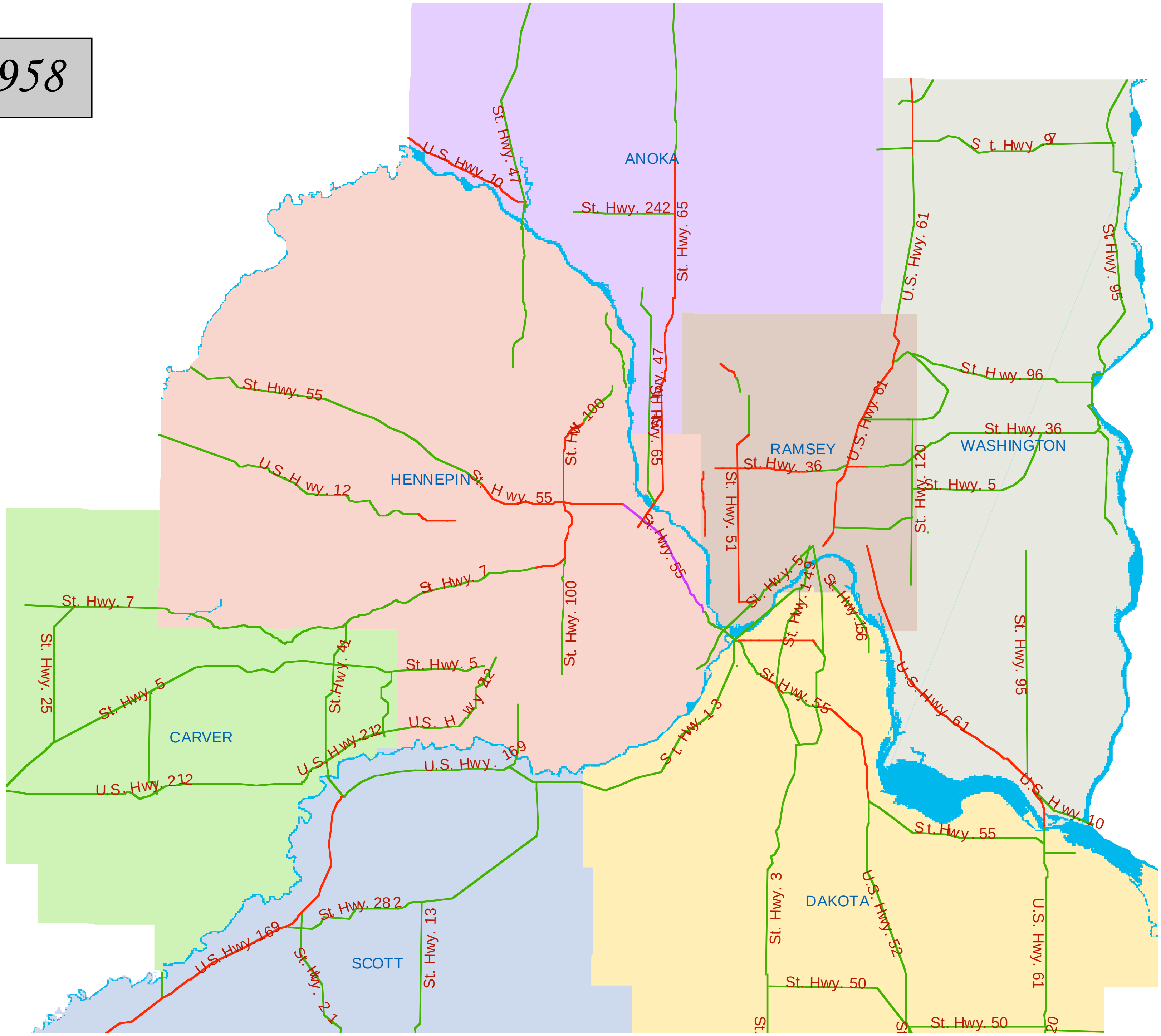
1958



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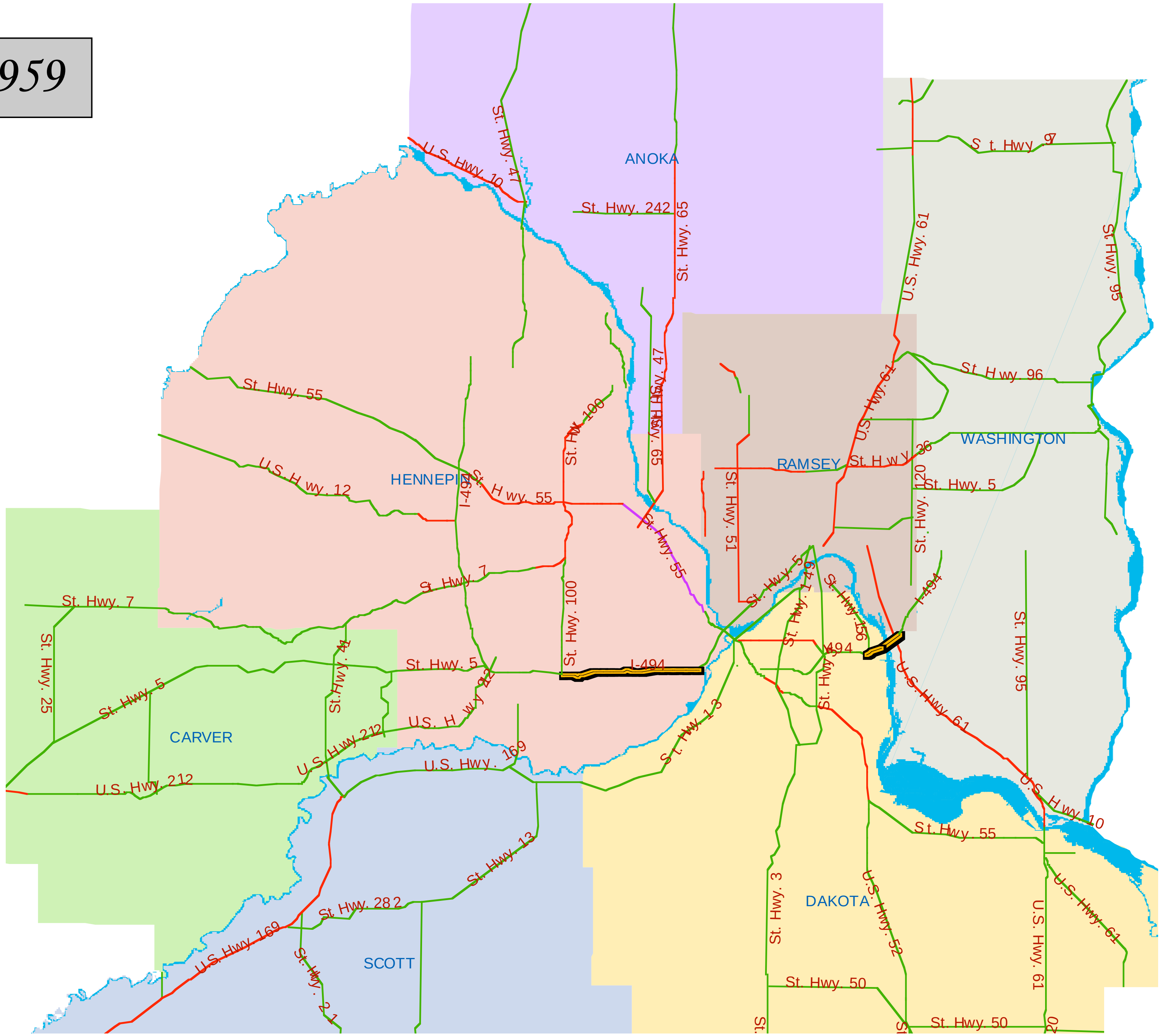
1959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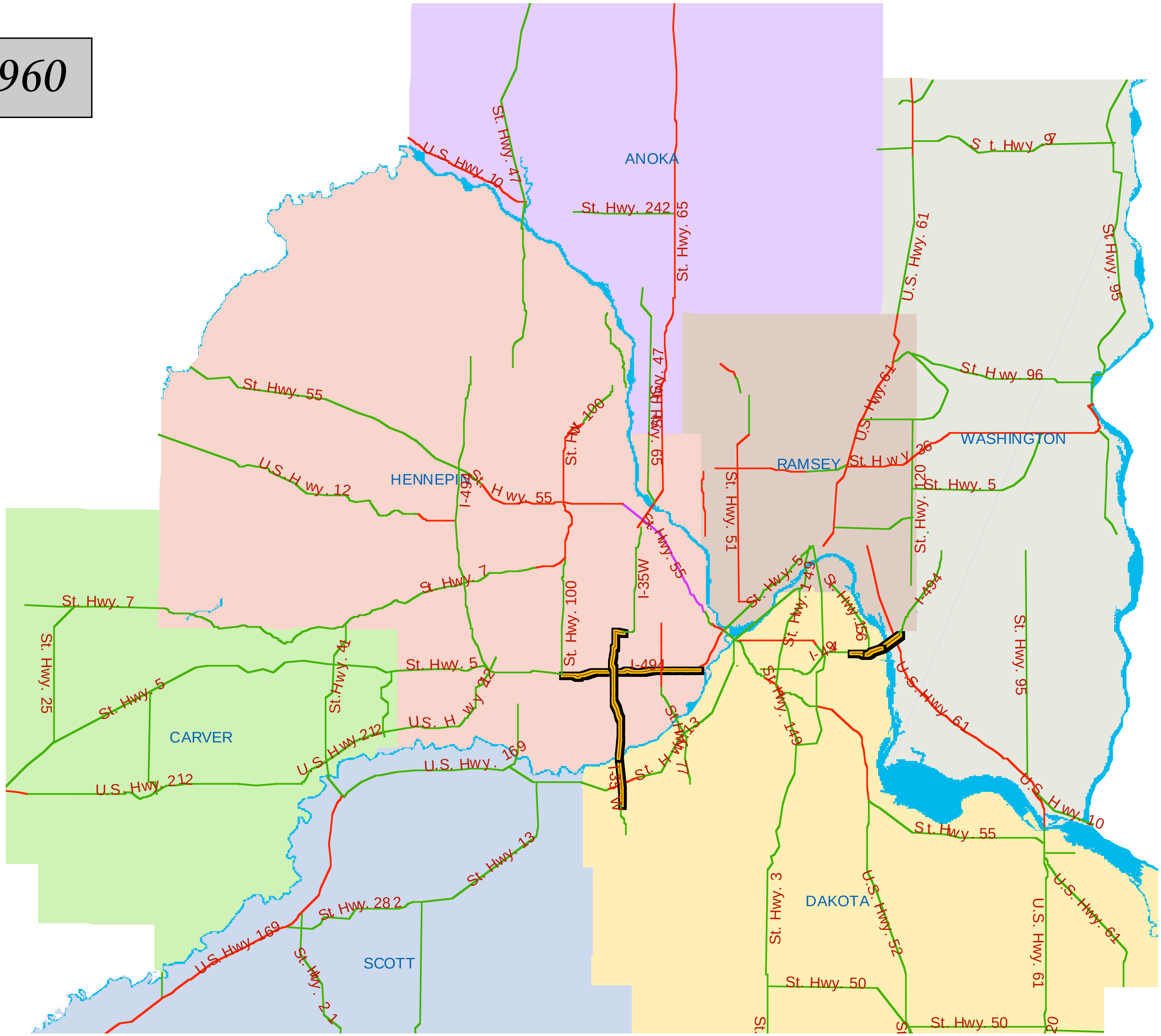
1960



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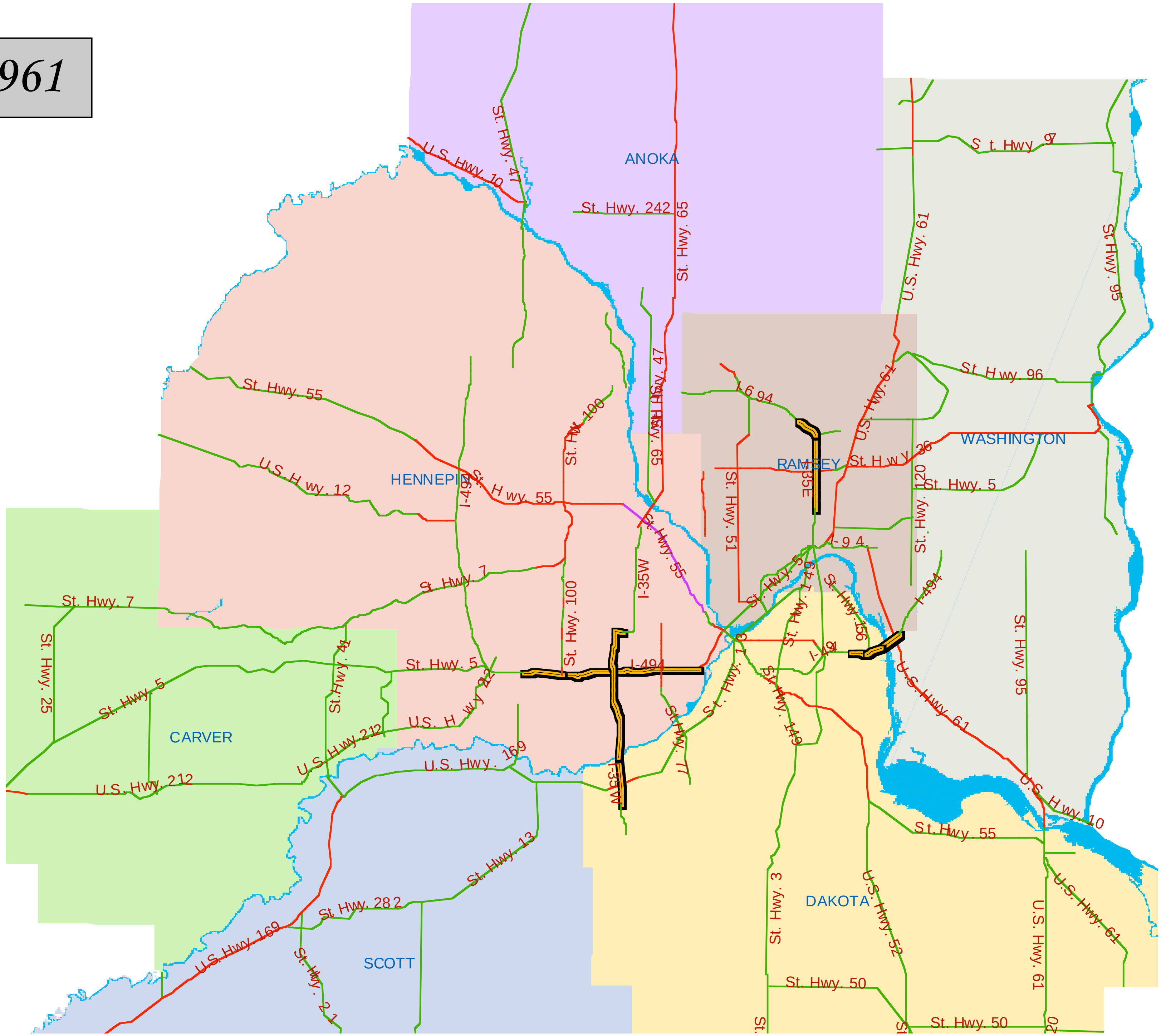
1961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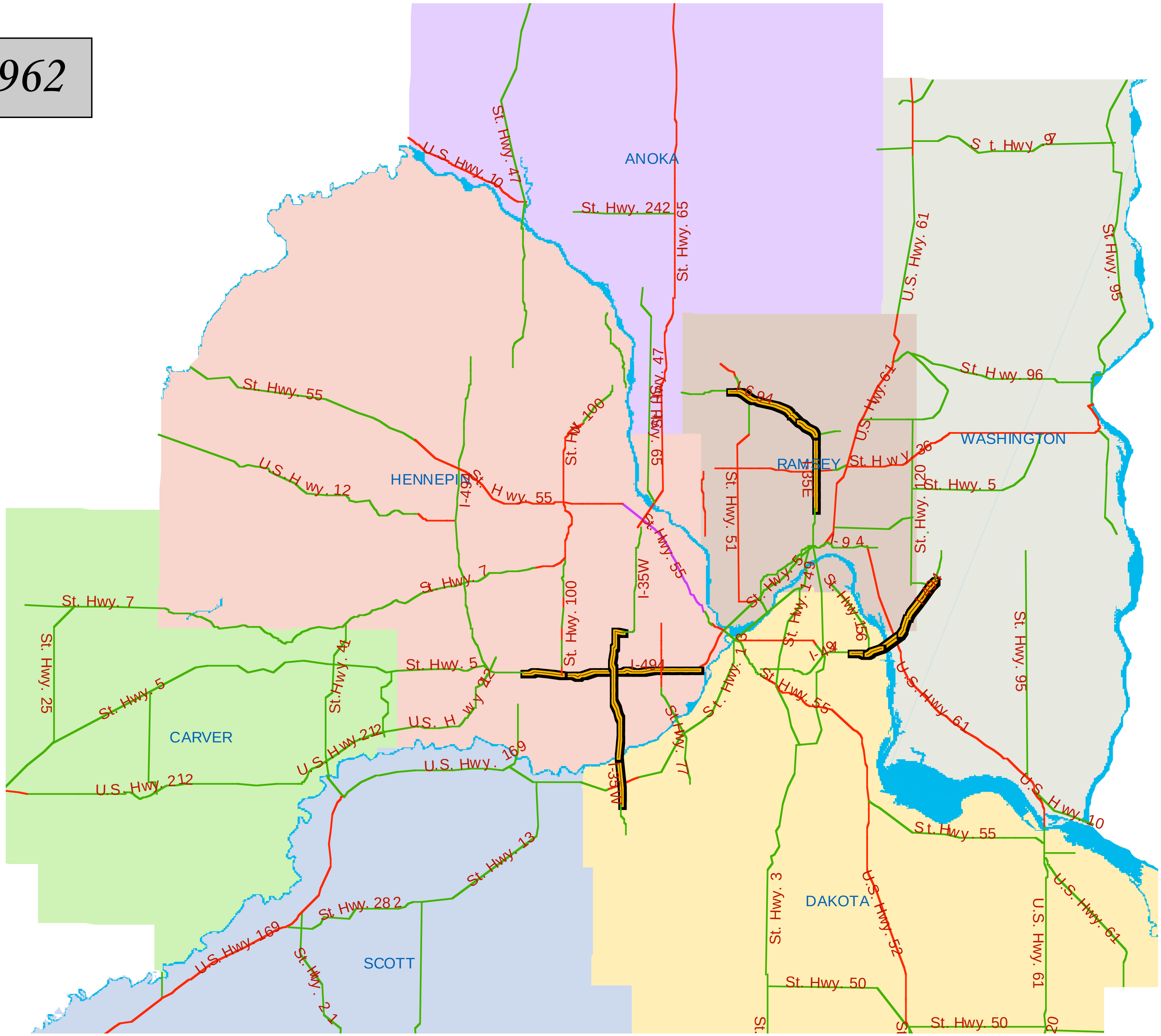
1962



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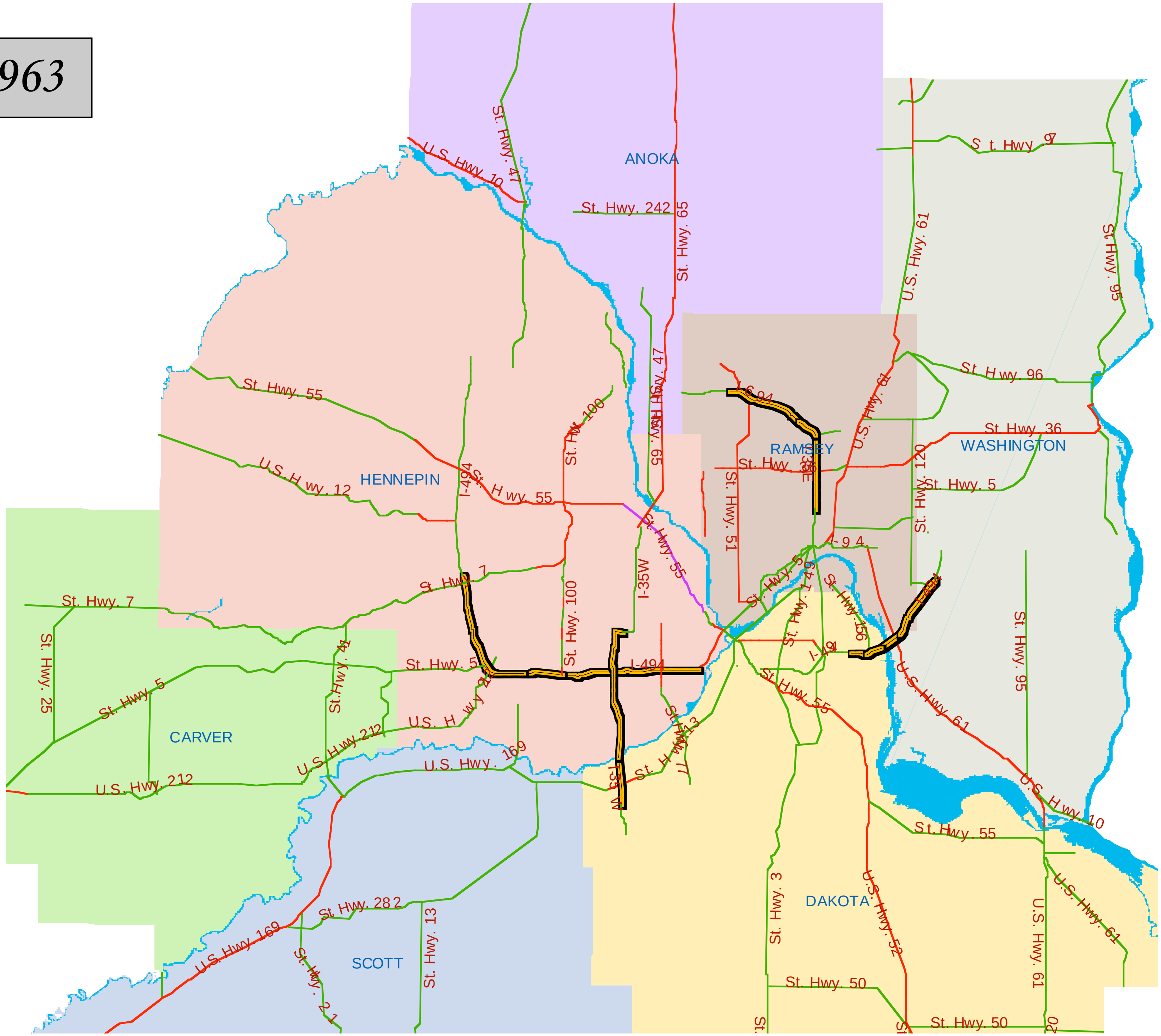
1963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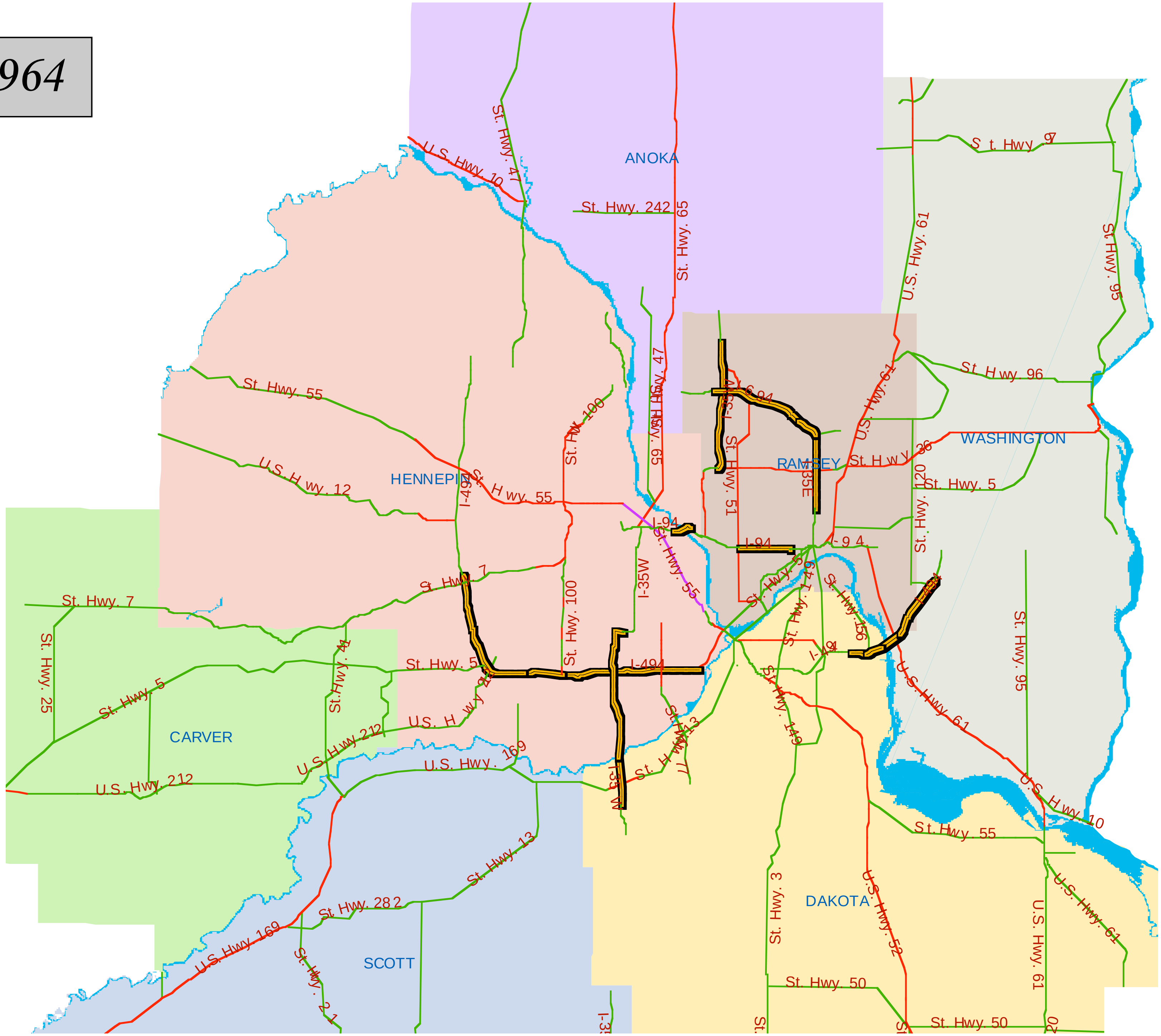
1964



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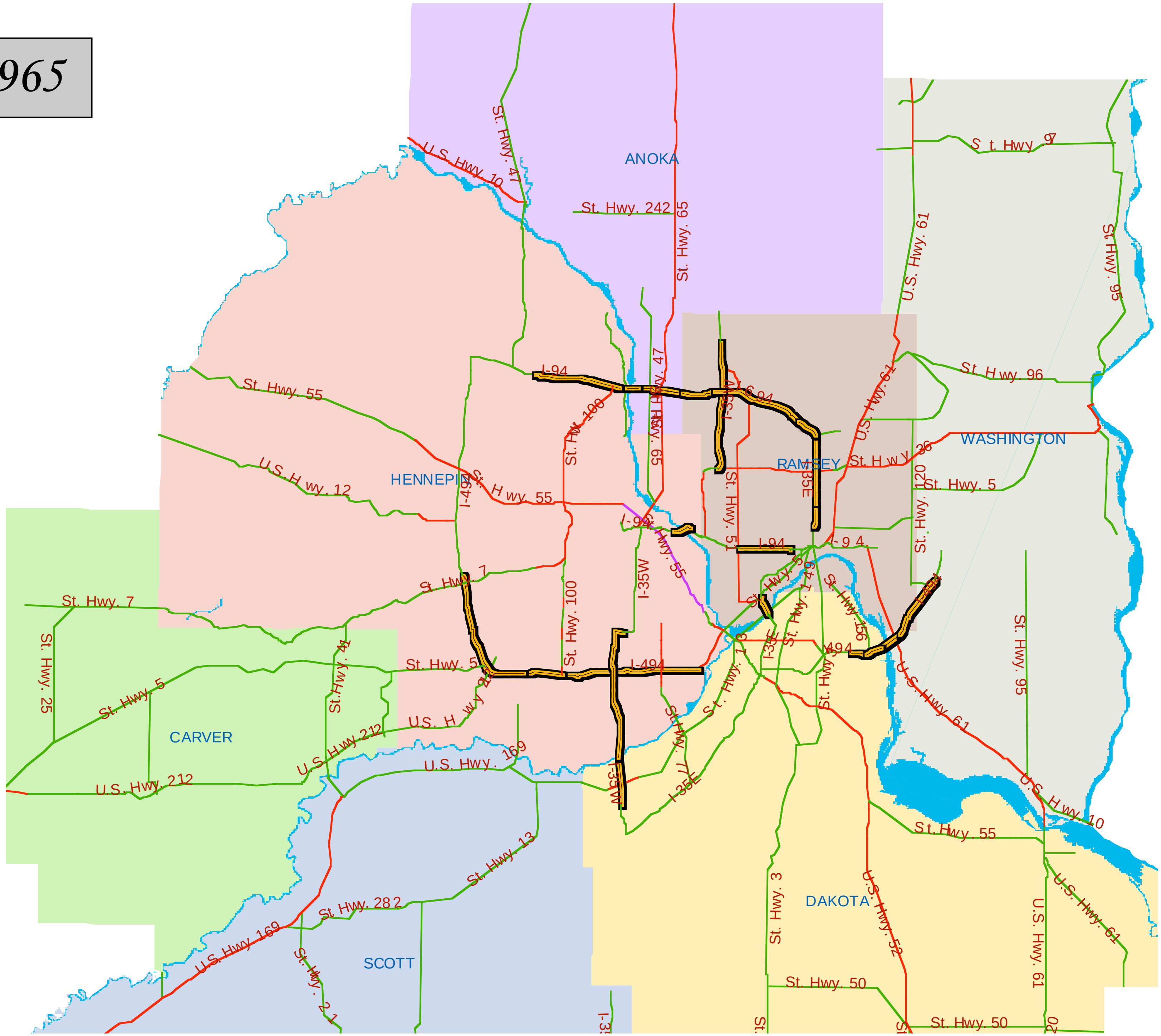
1965



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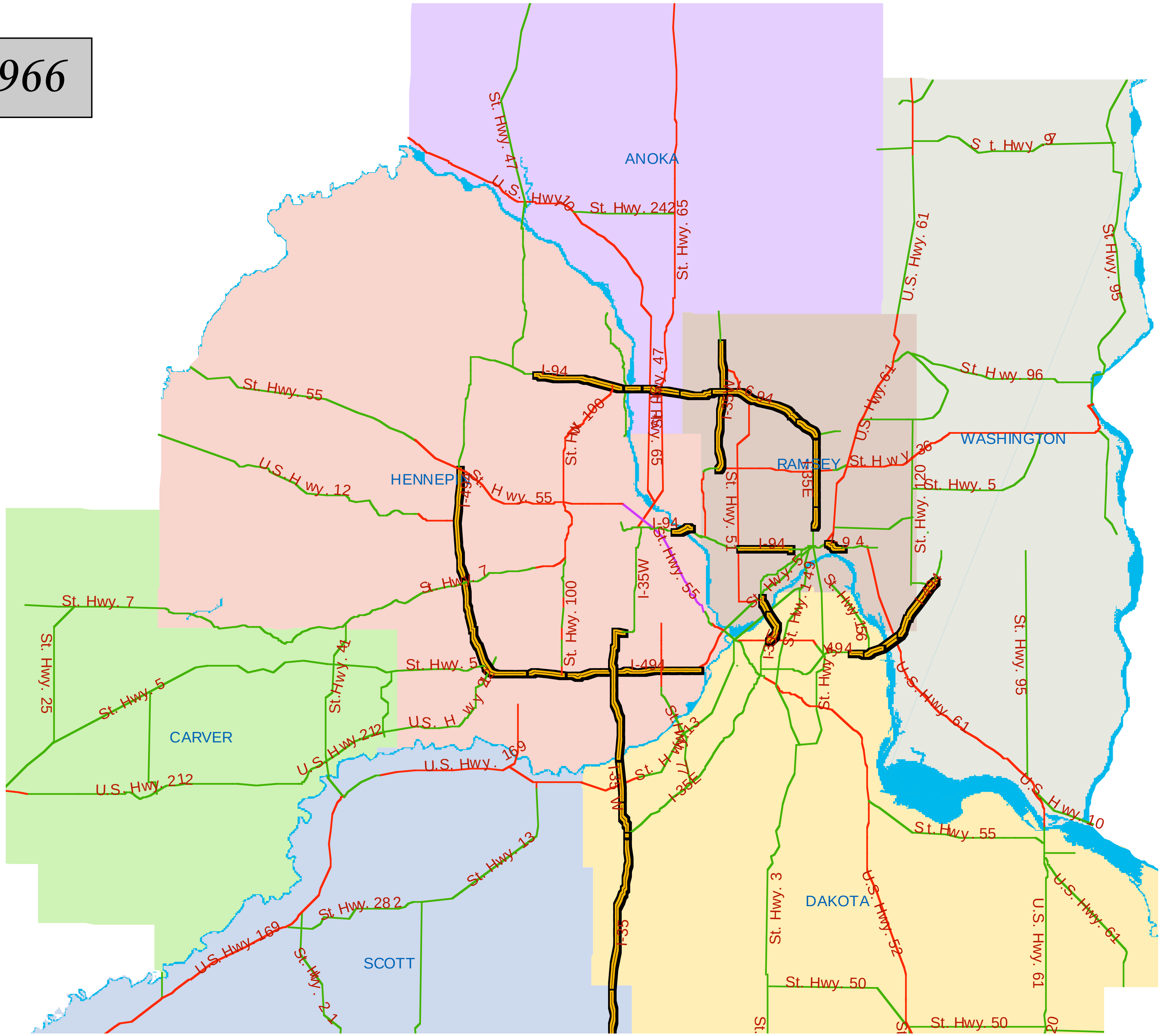
1966



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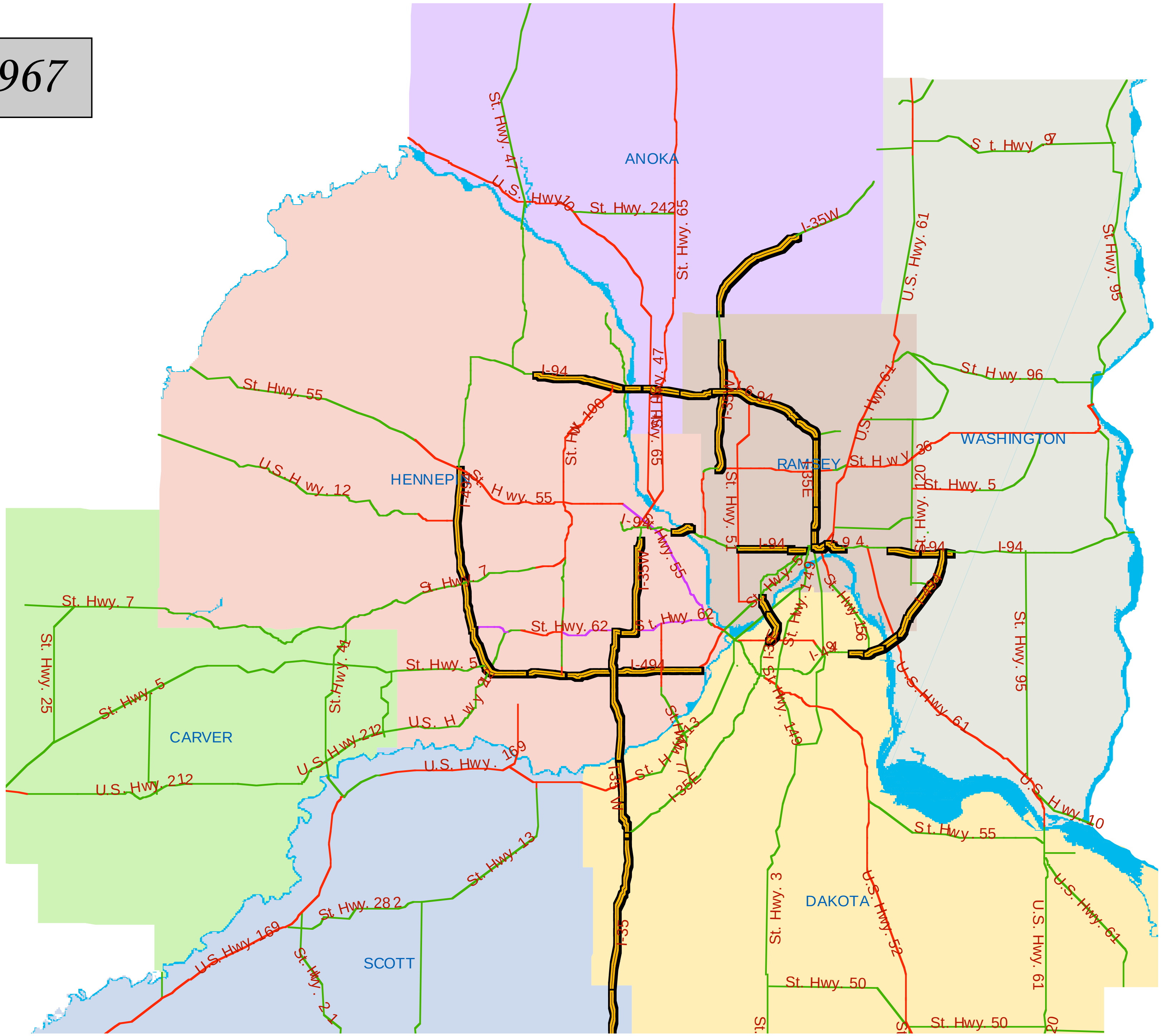
1967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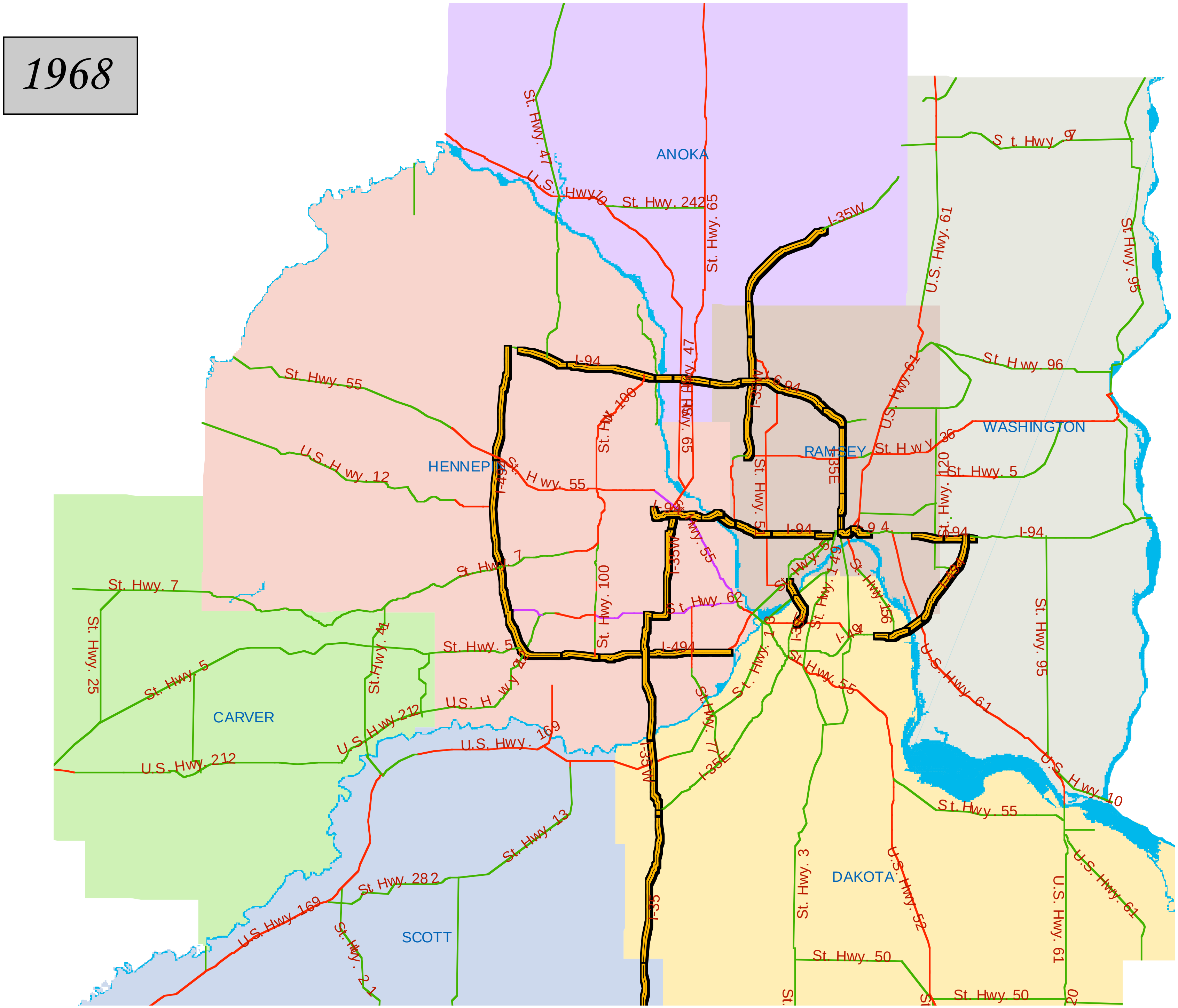
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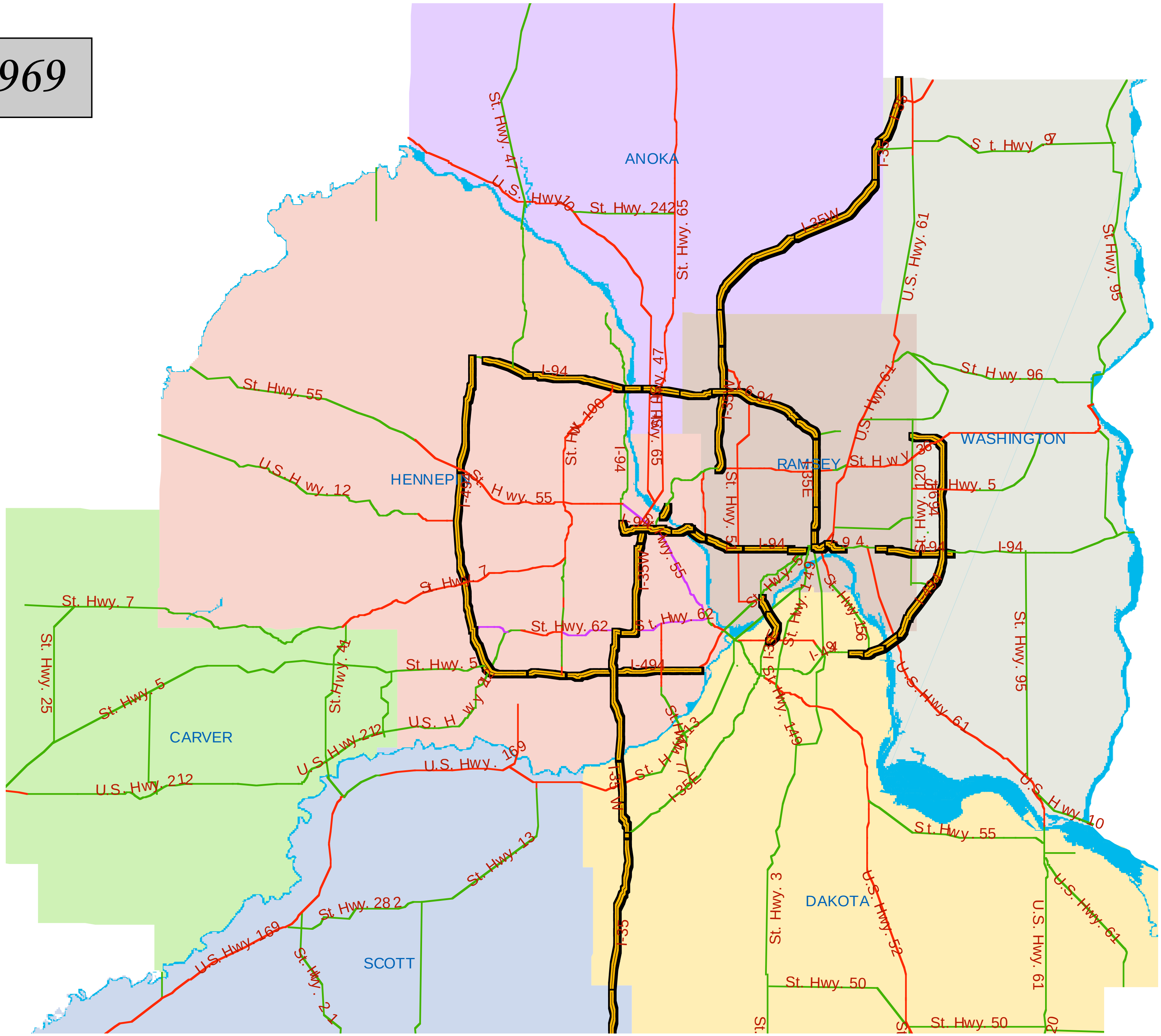

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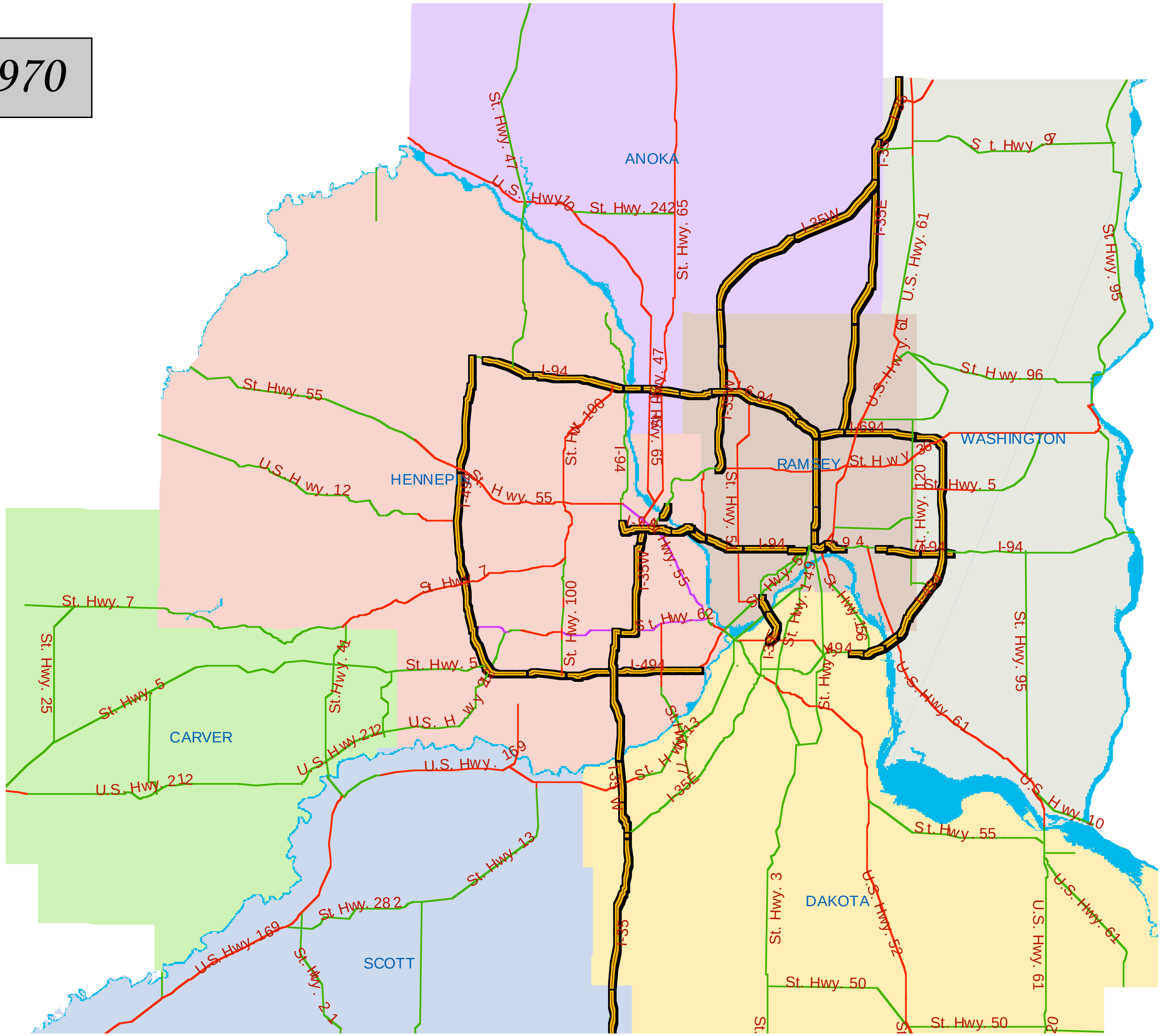

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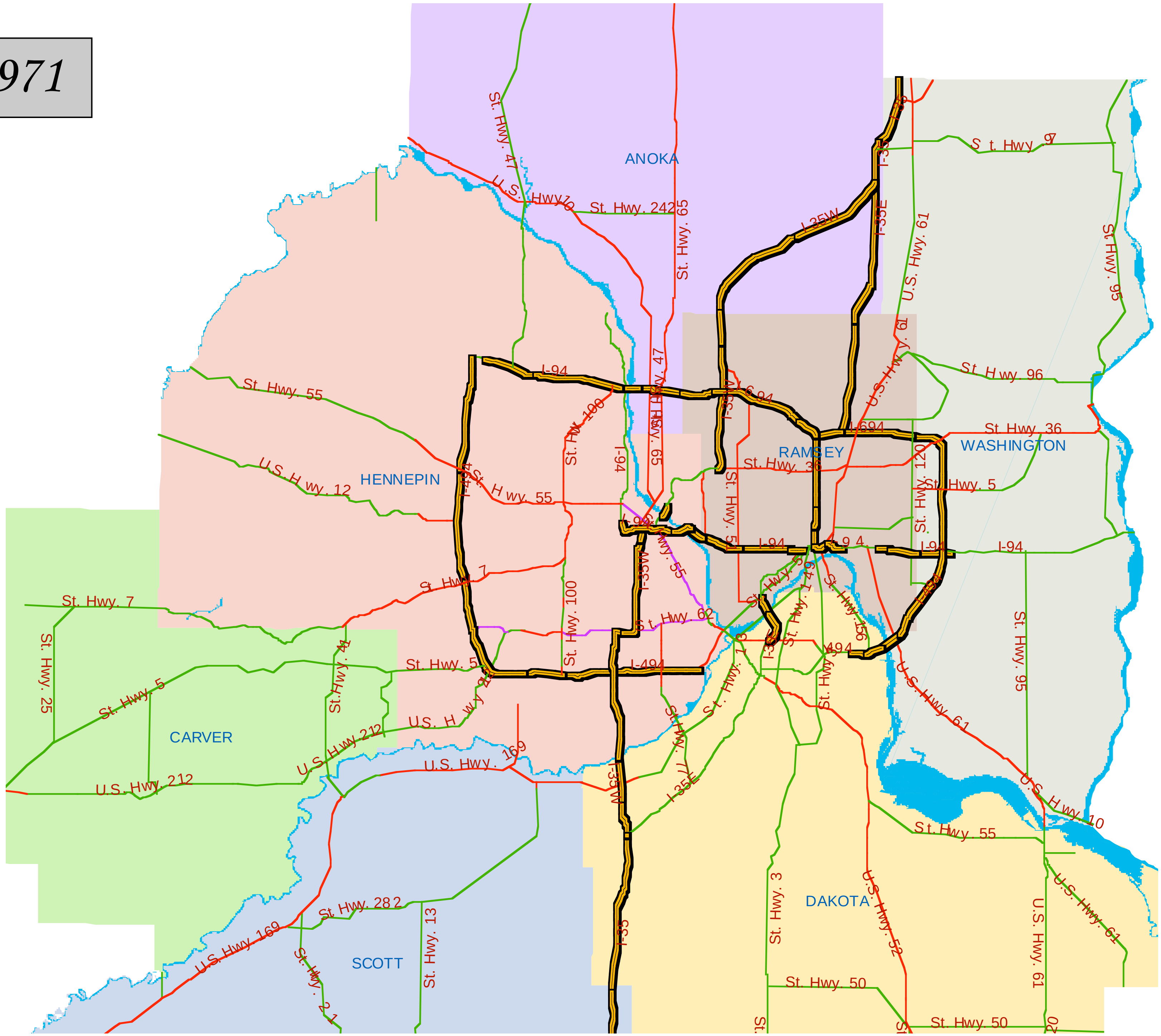

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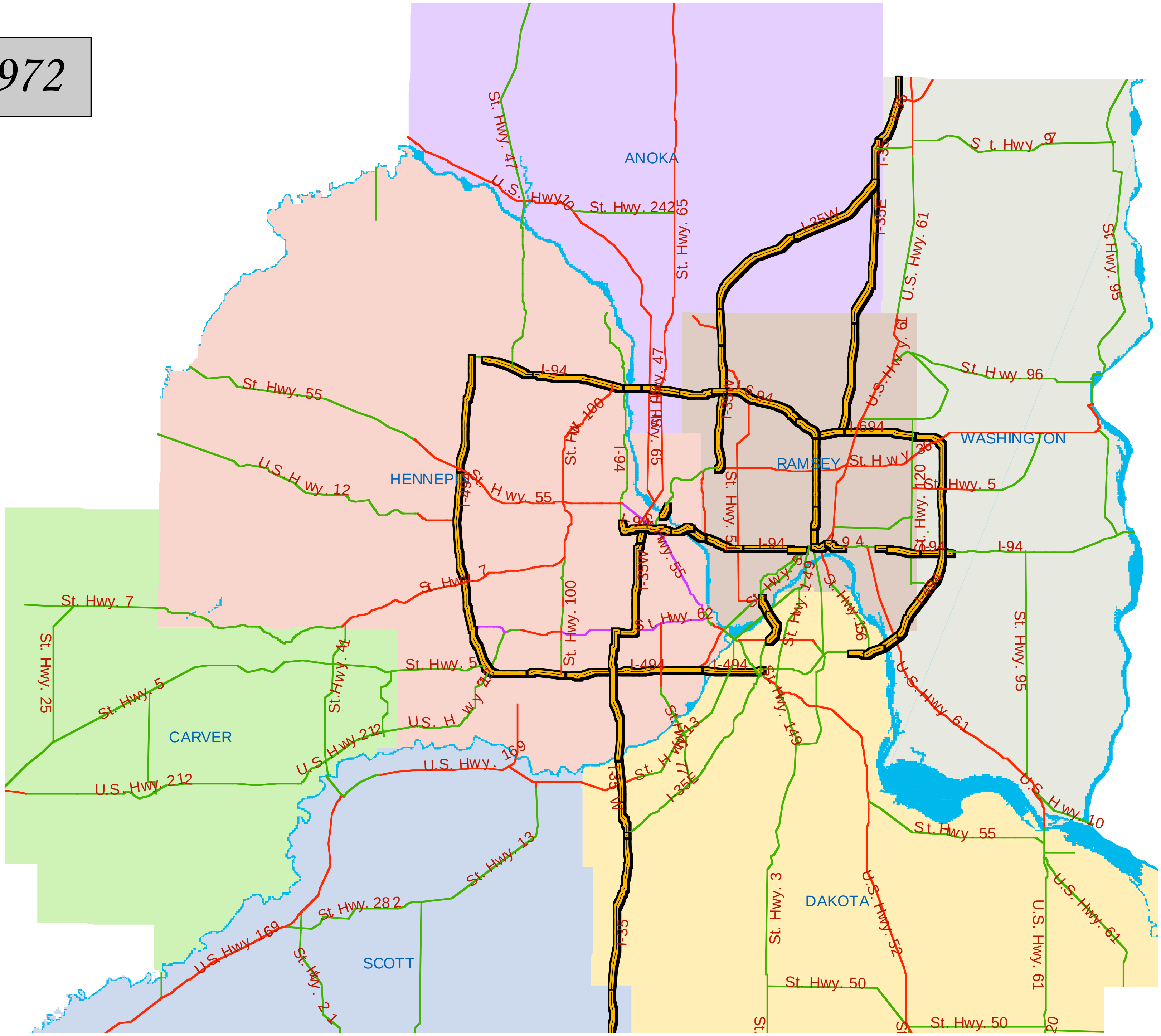
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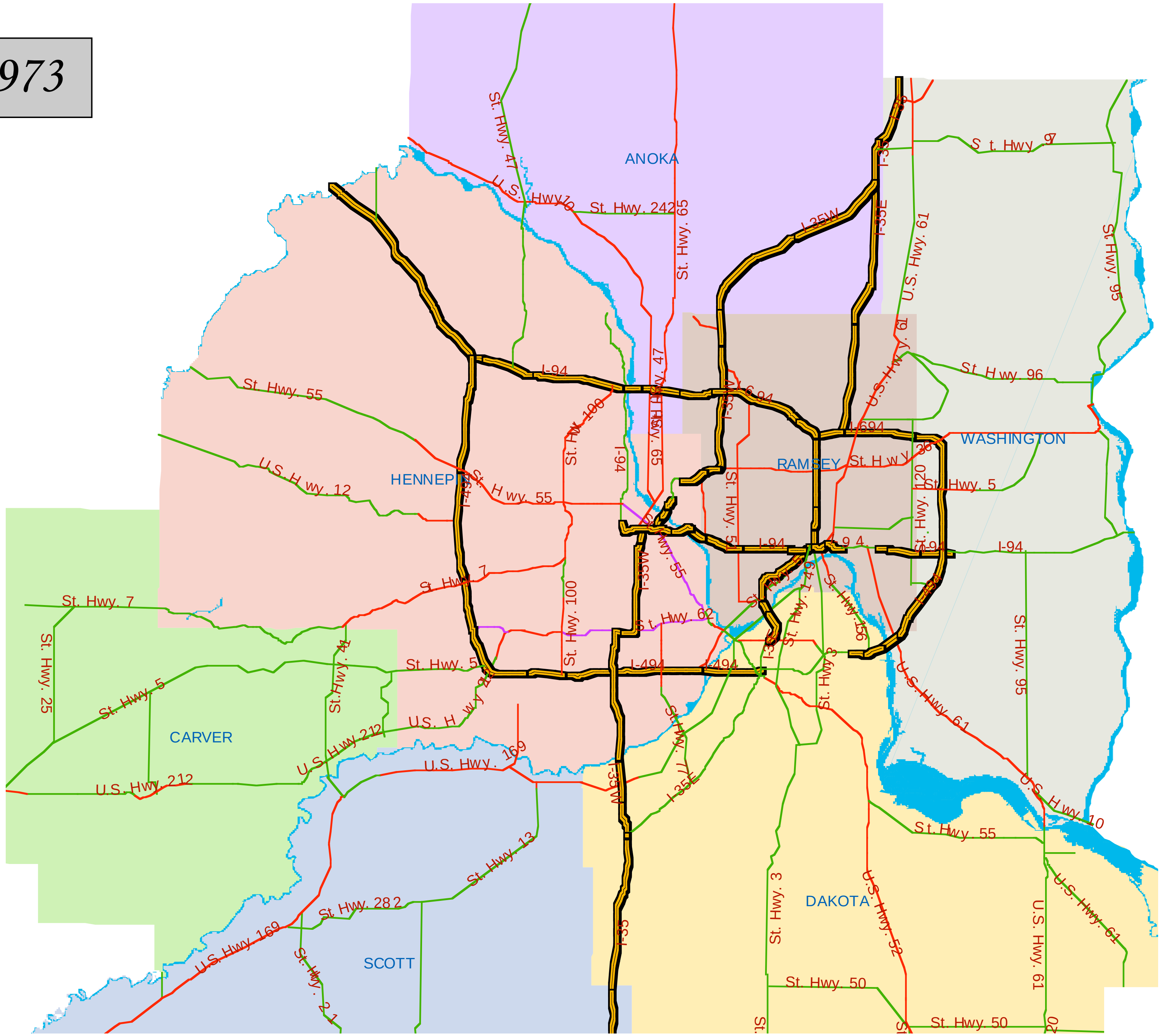
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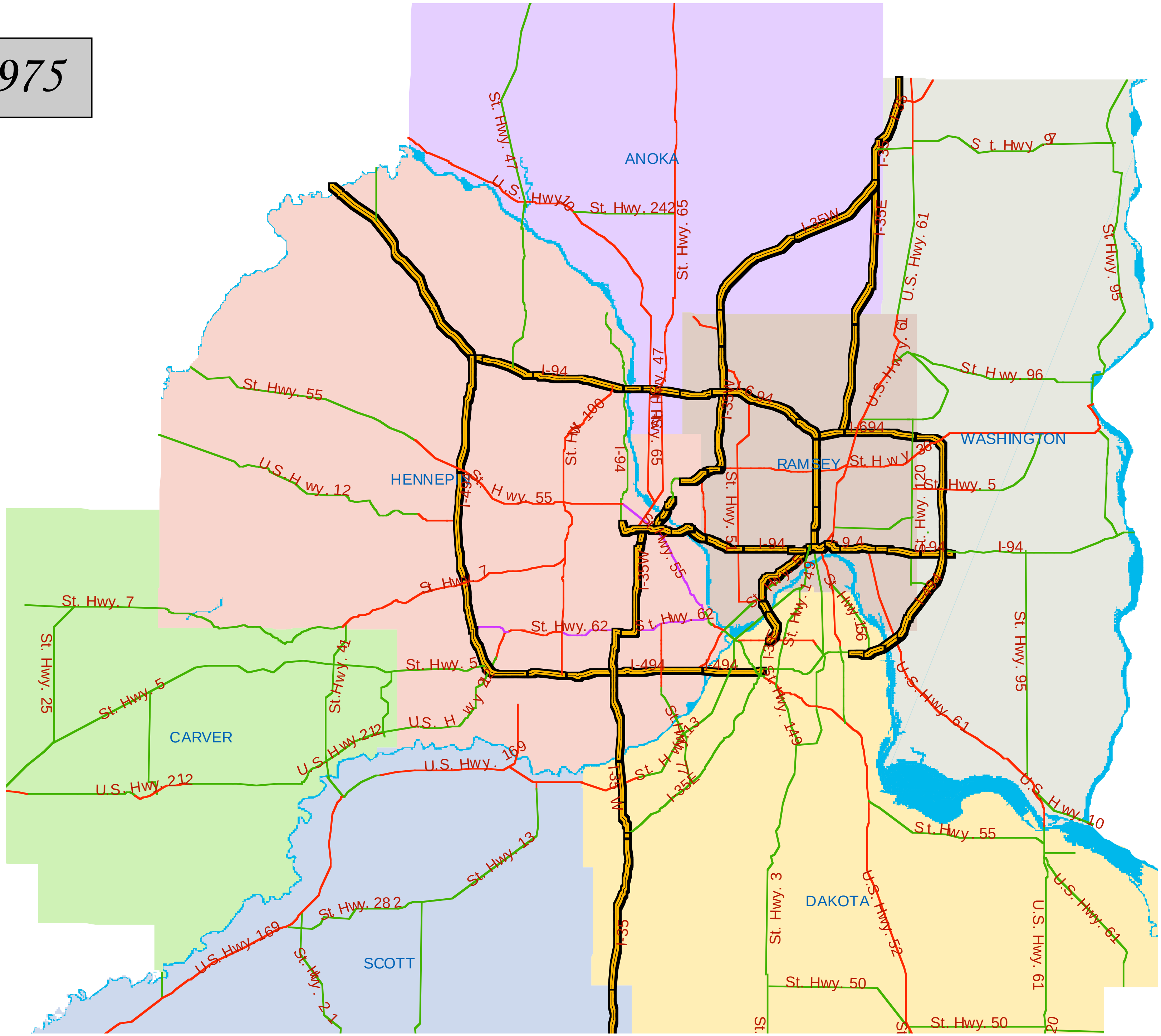

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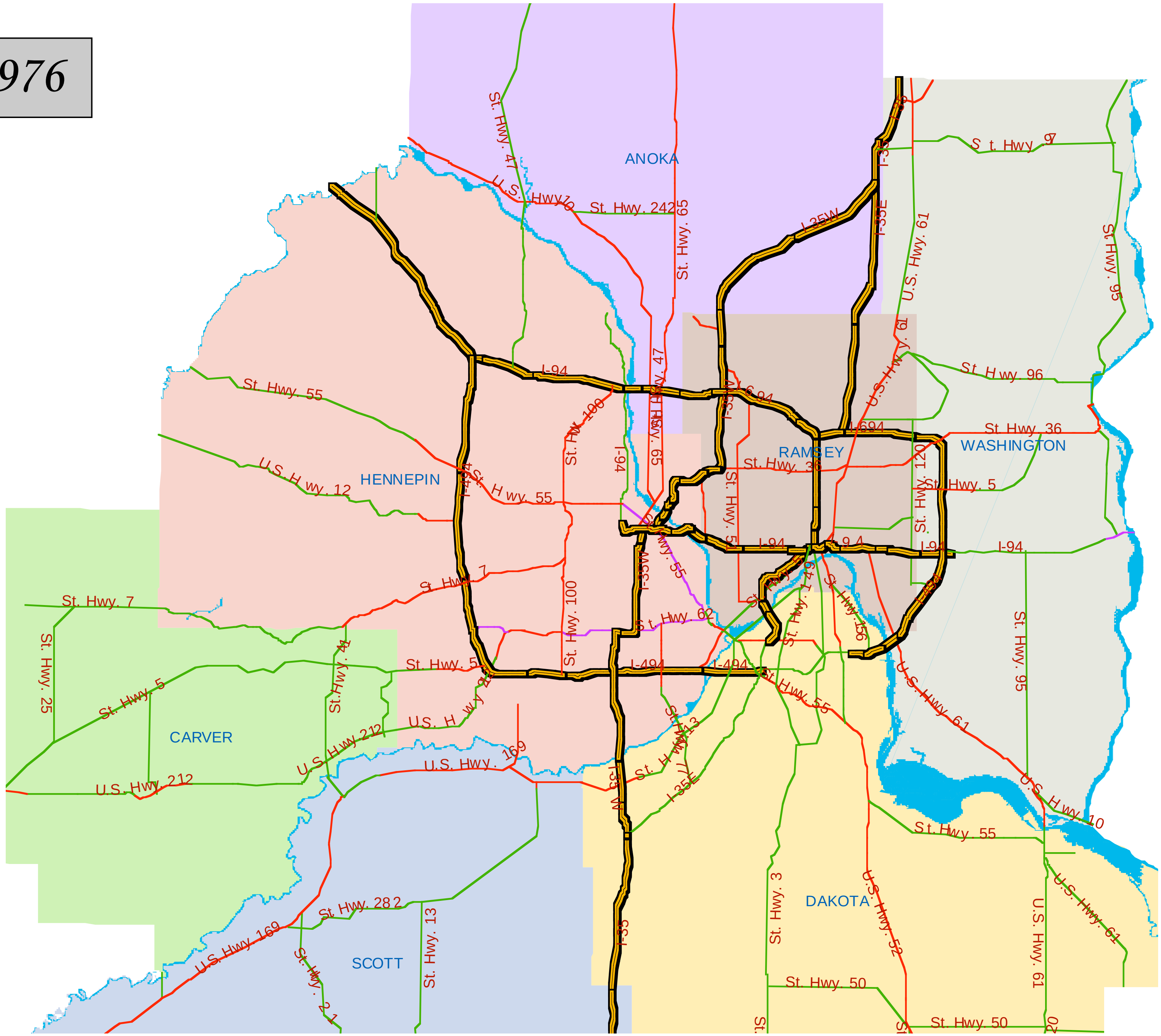
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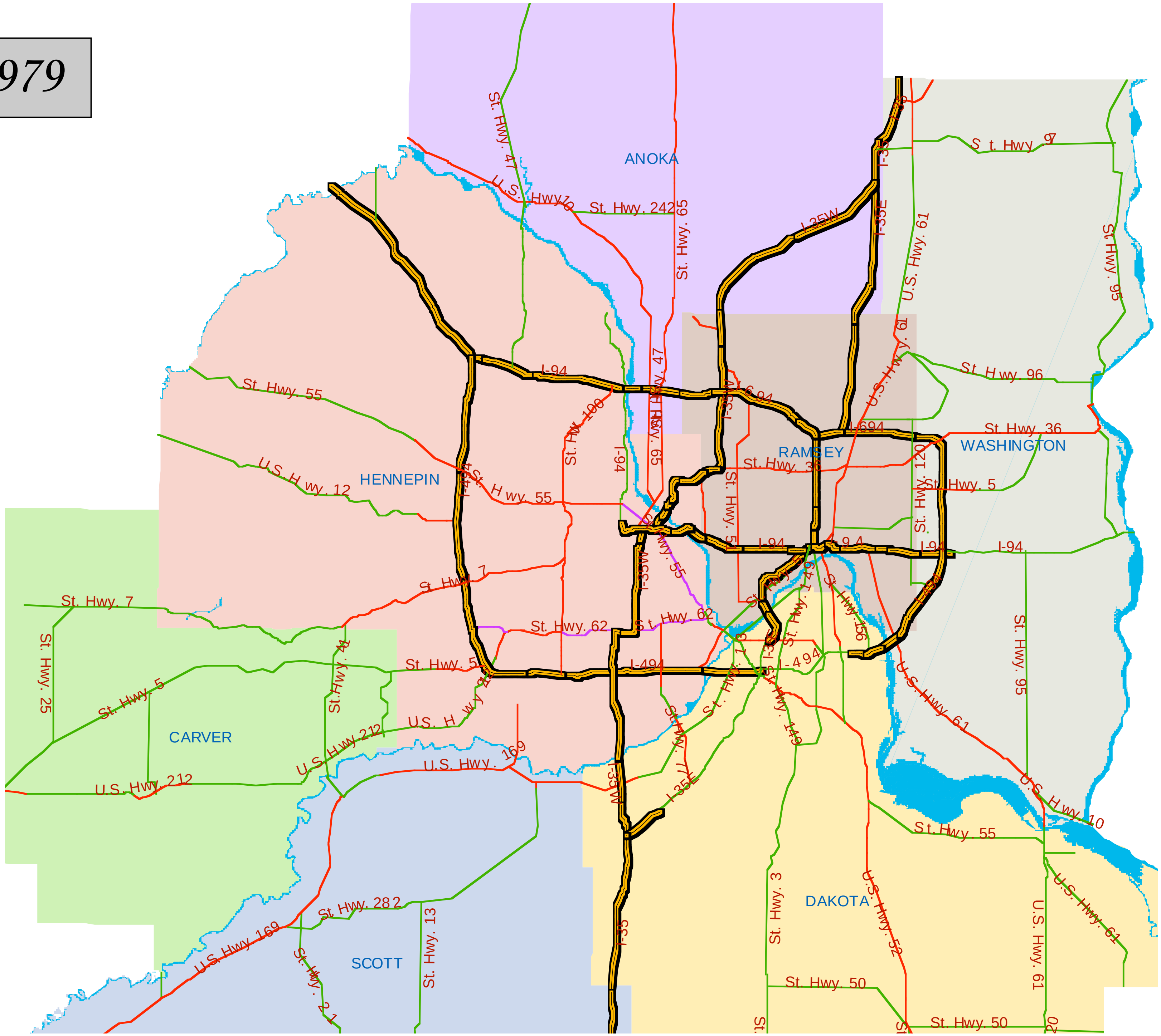
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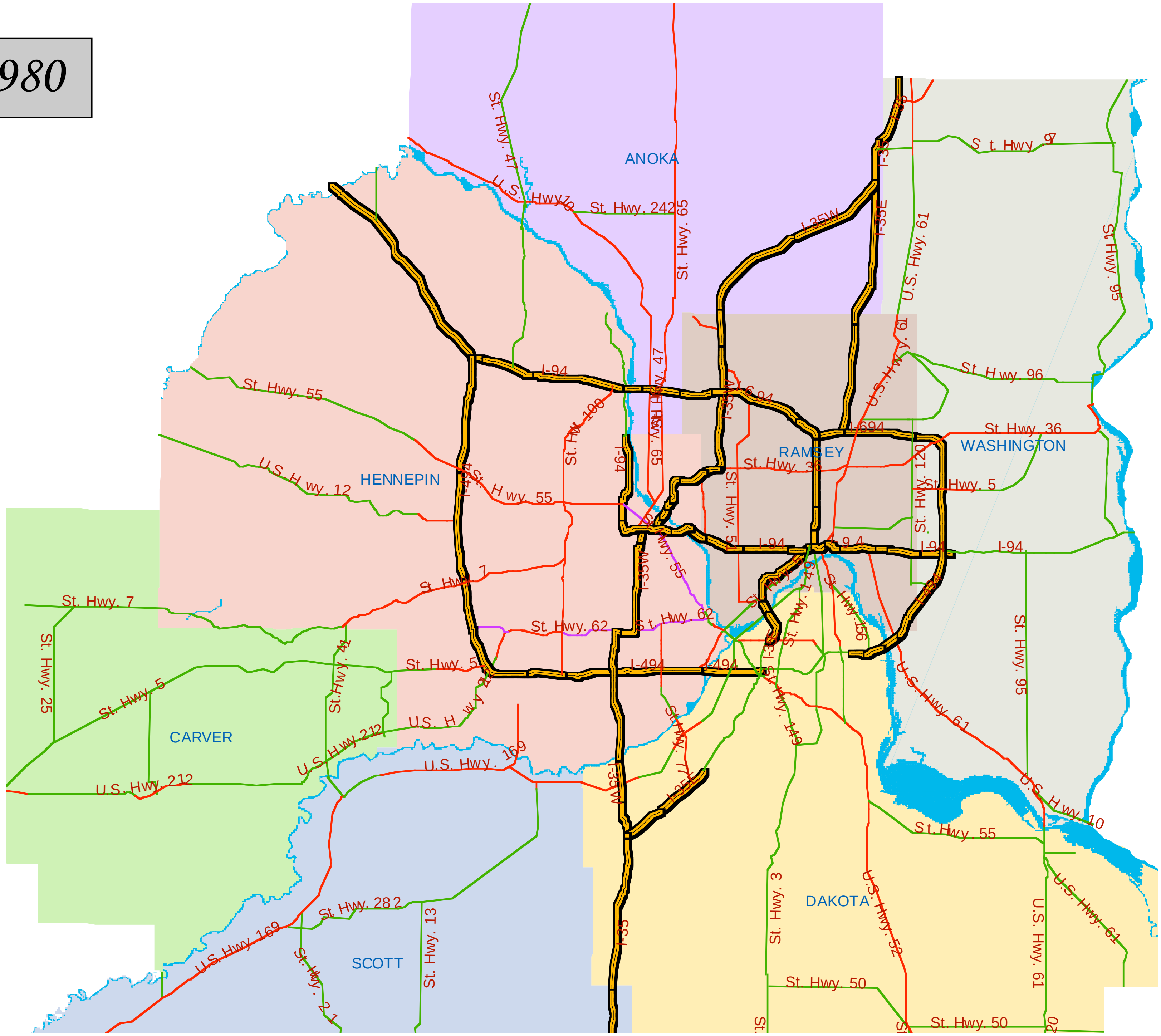
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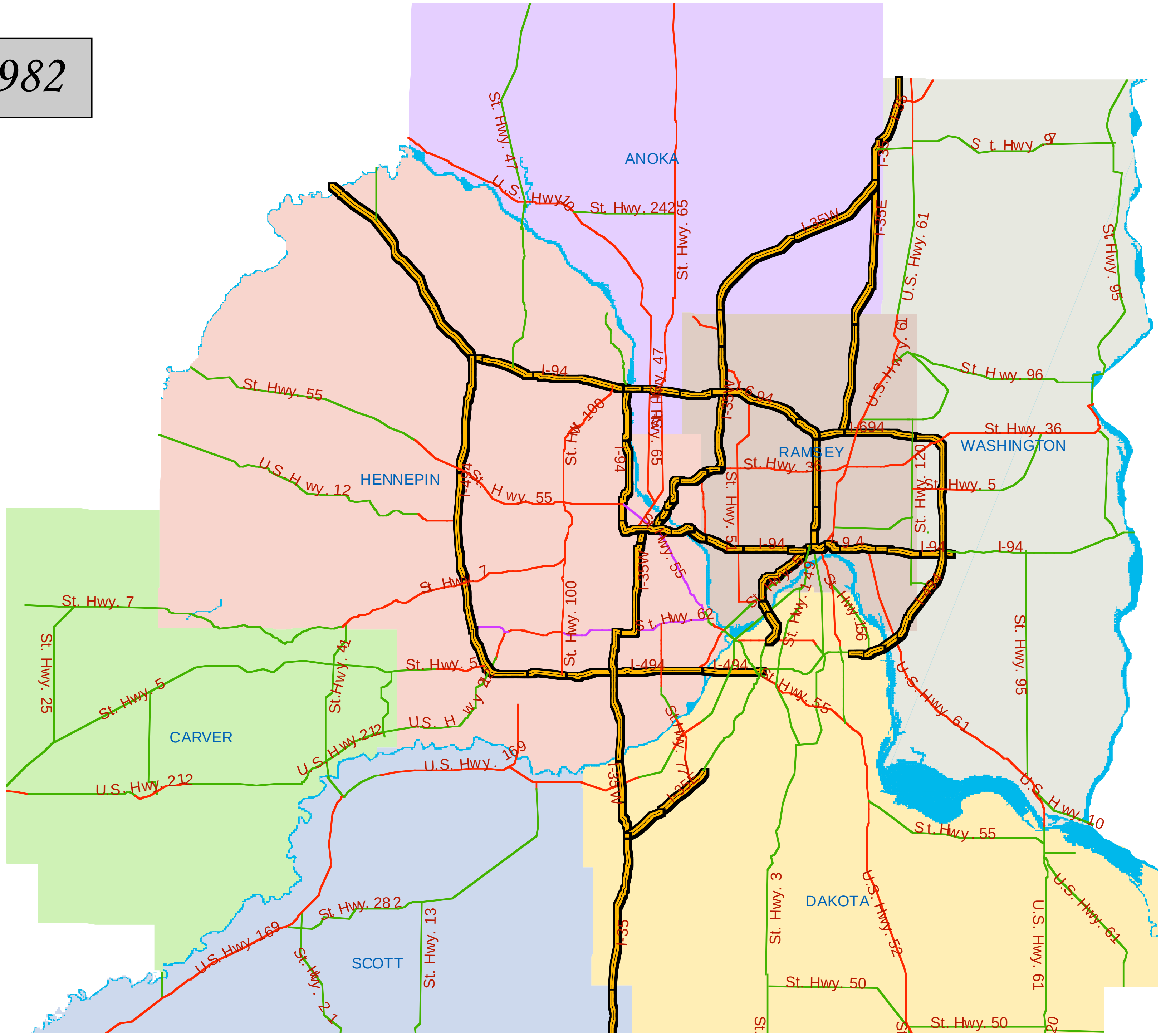
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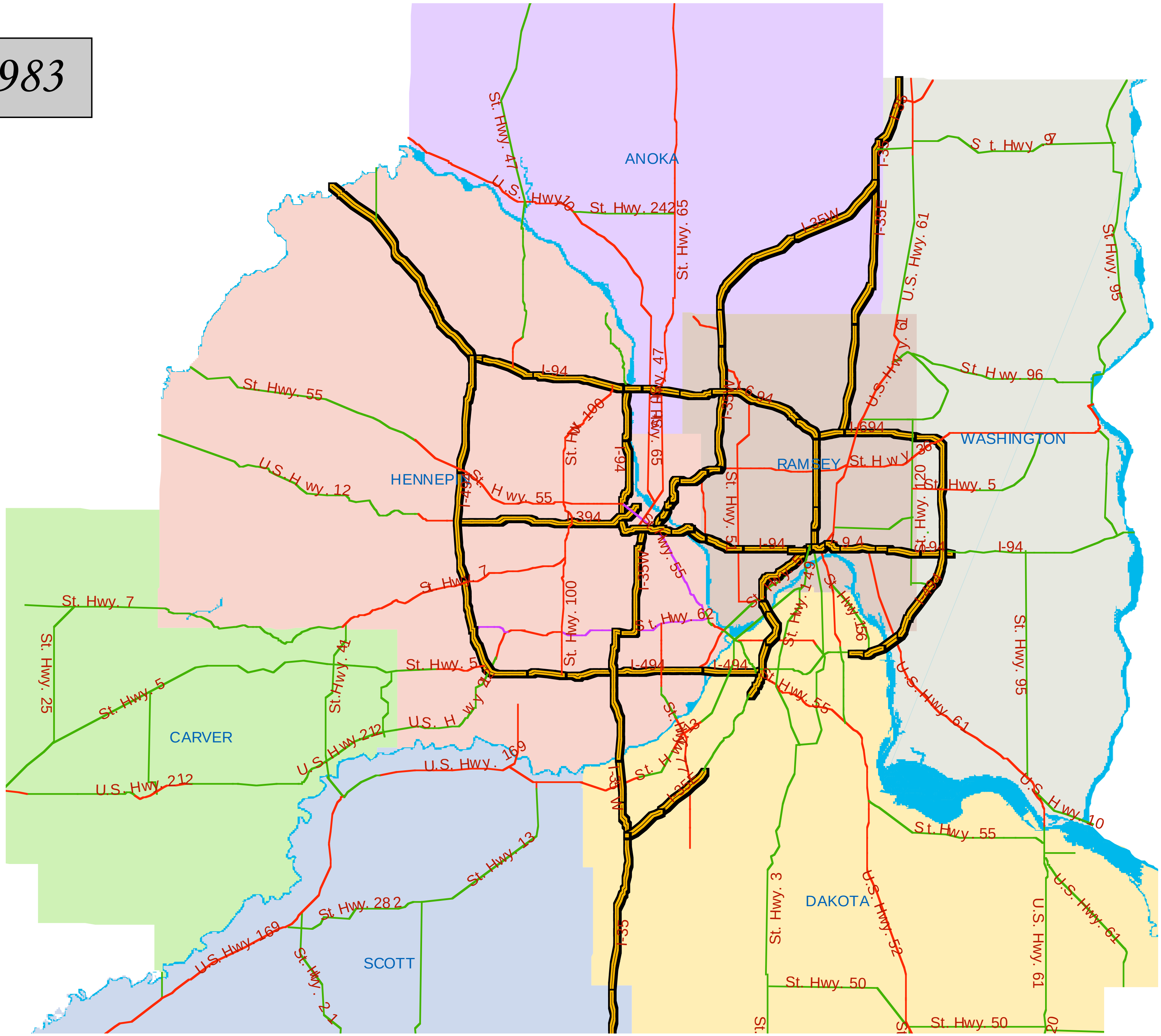

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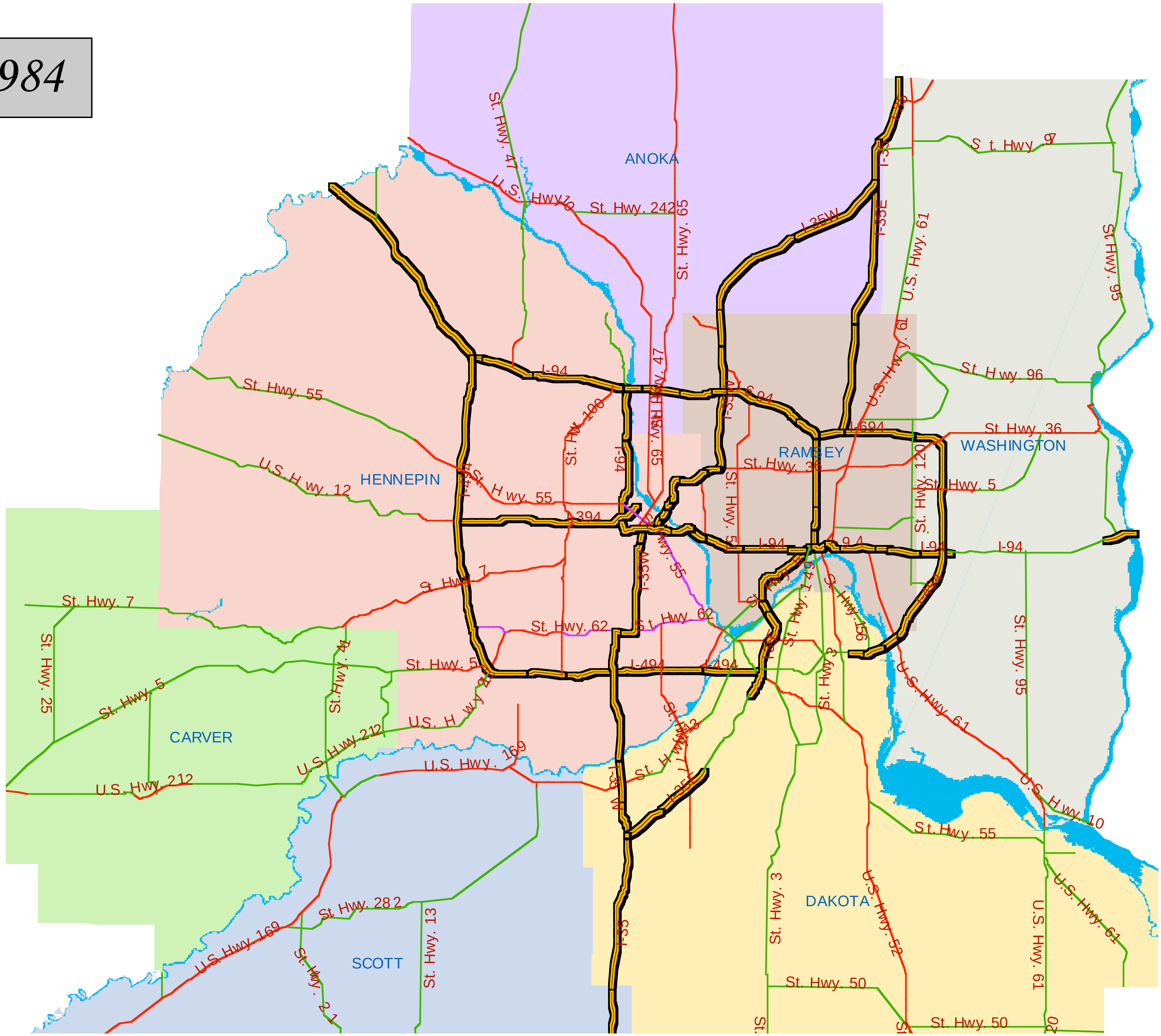

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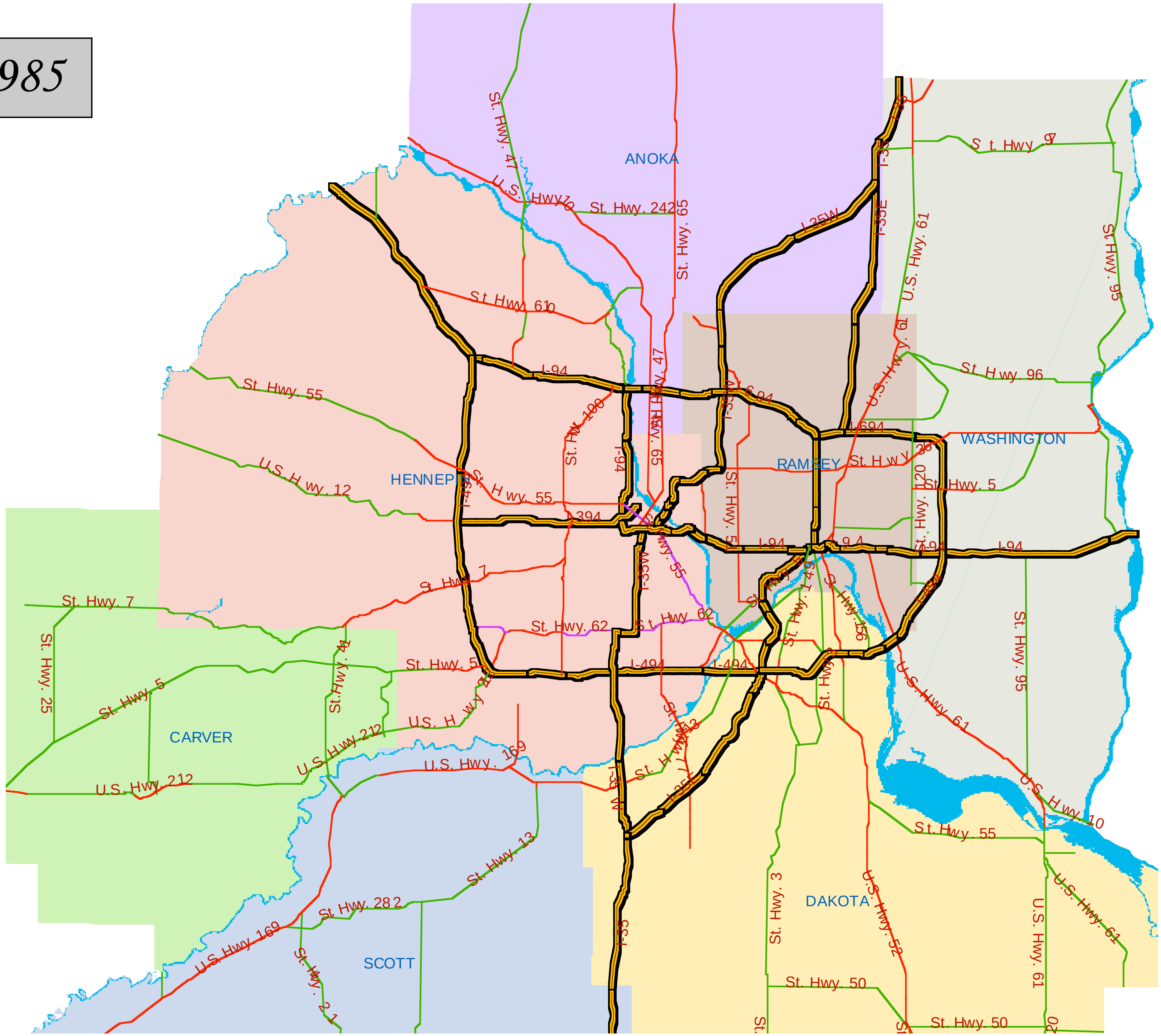
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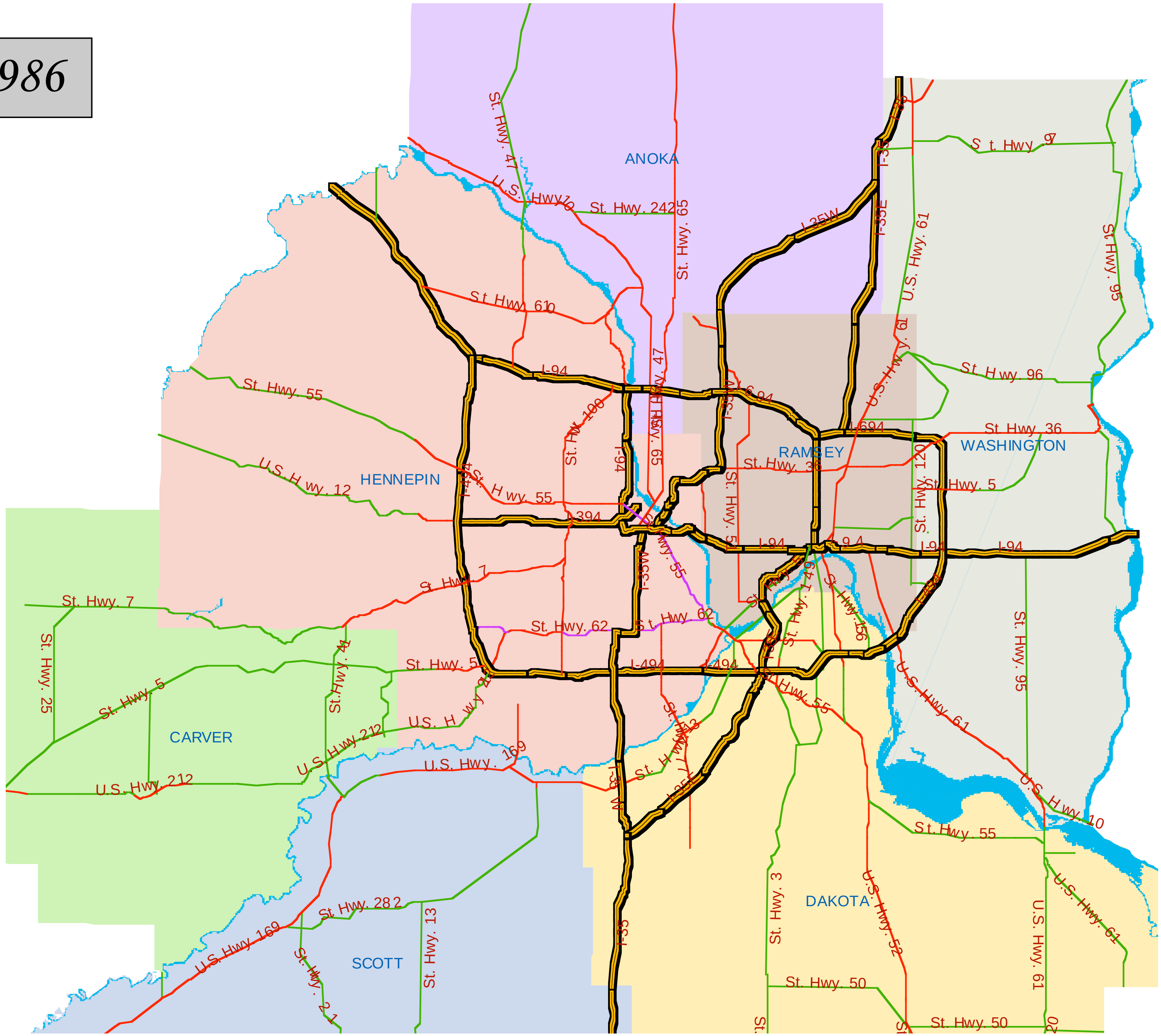
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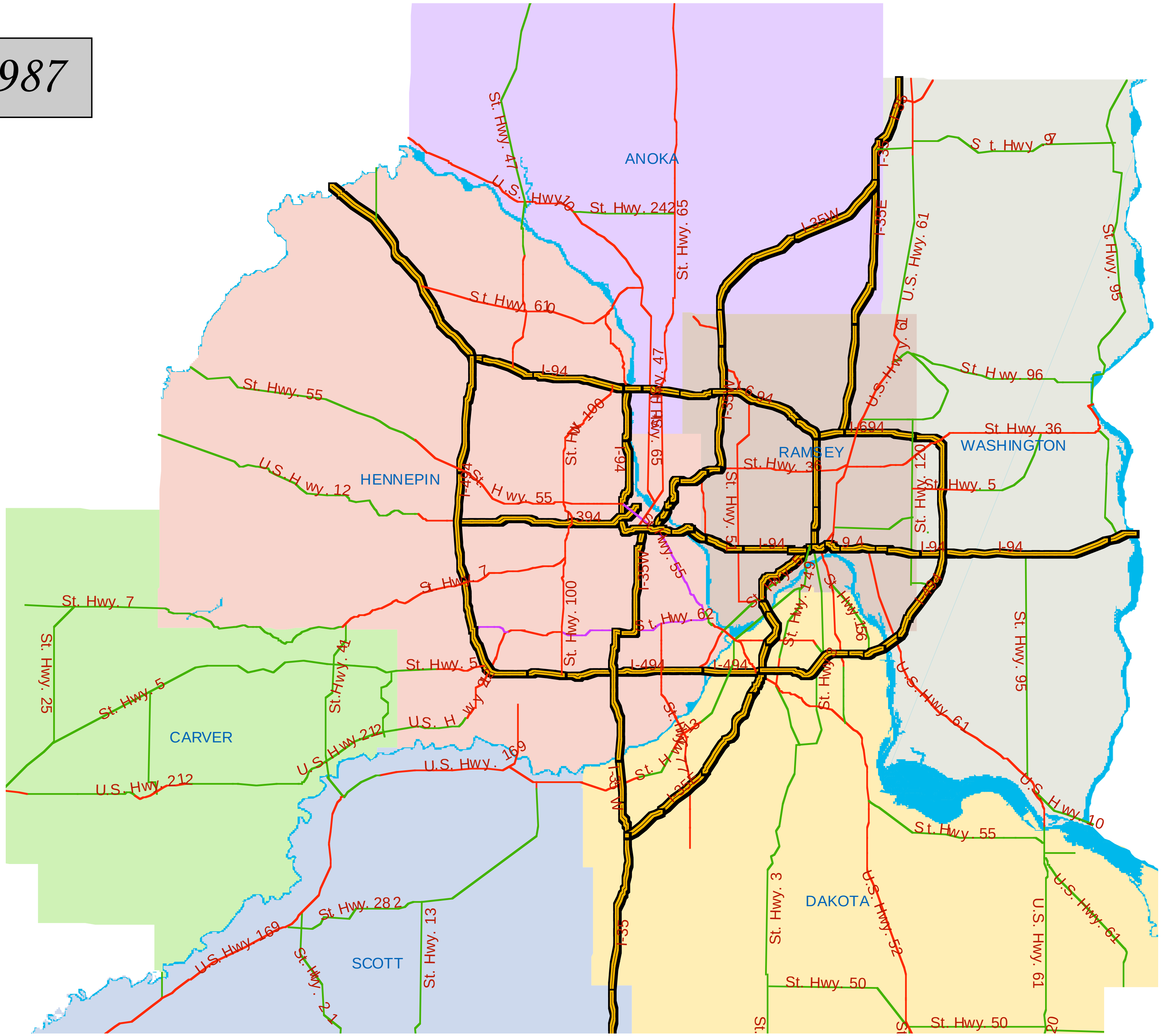
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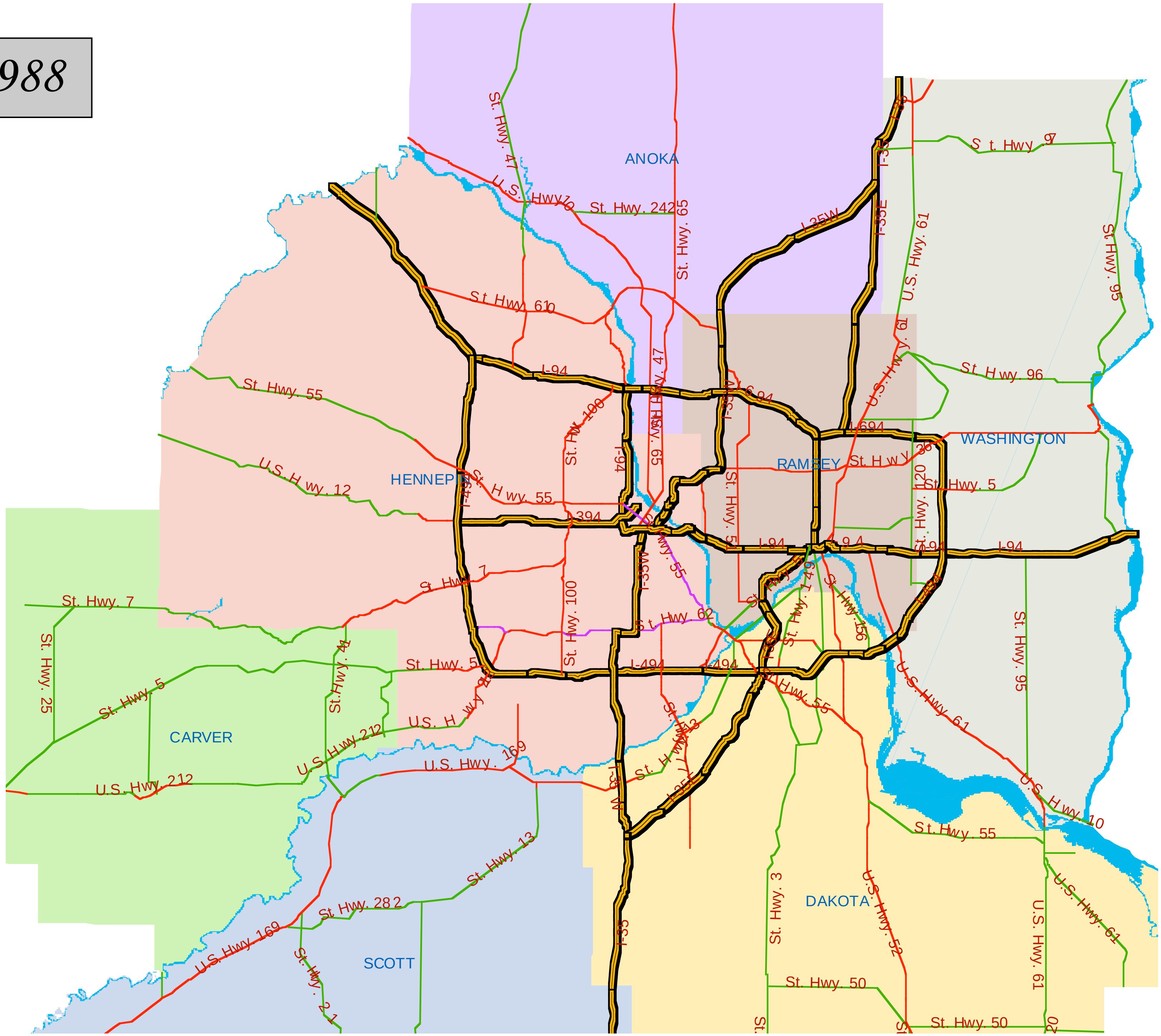

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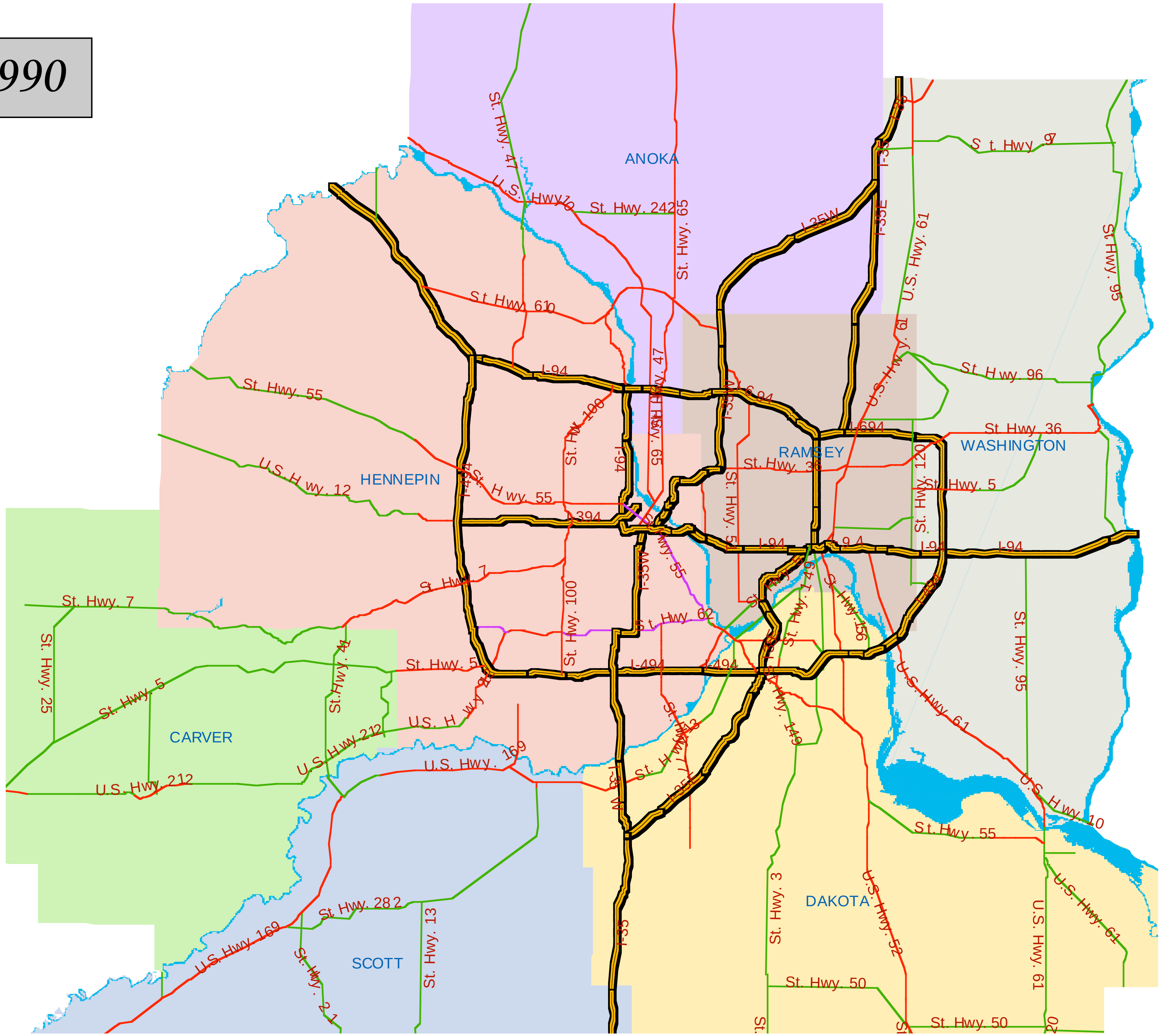

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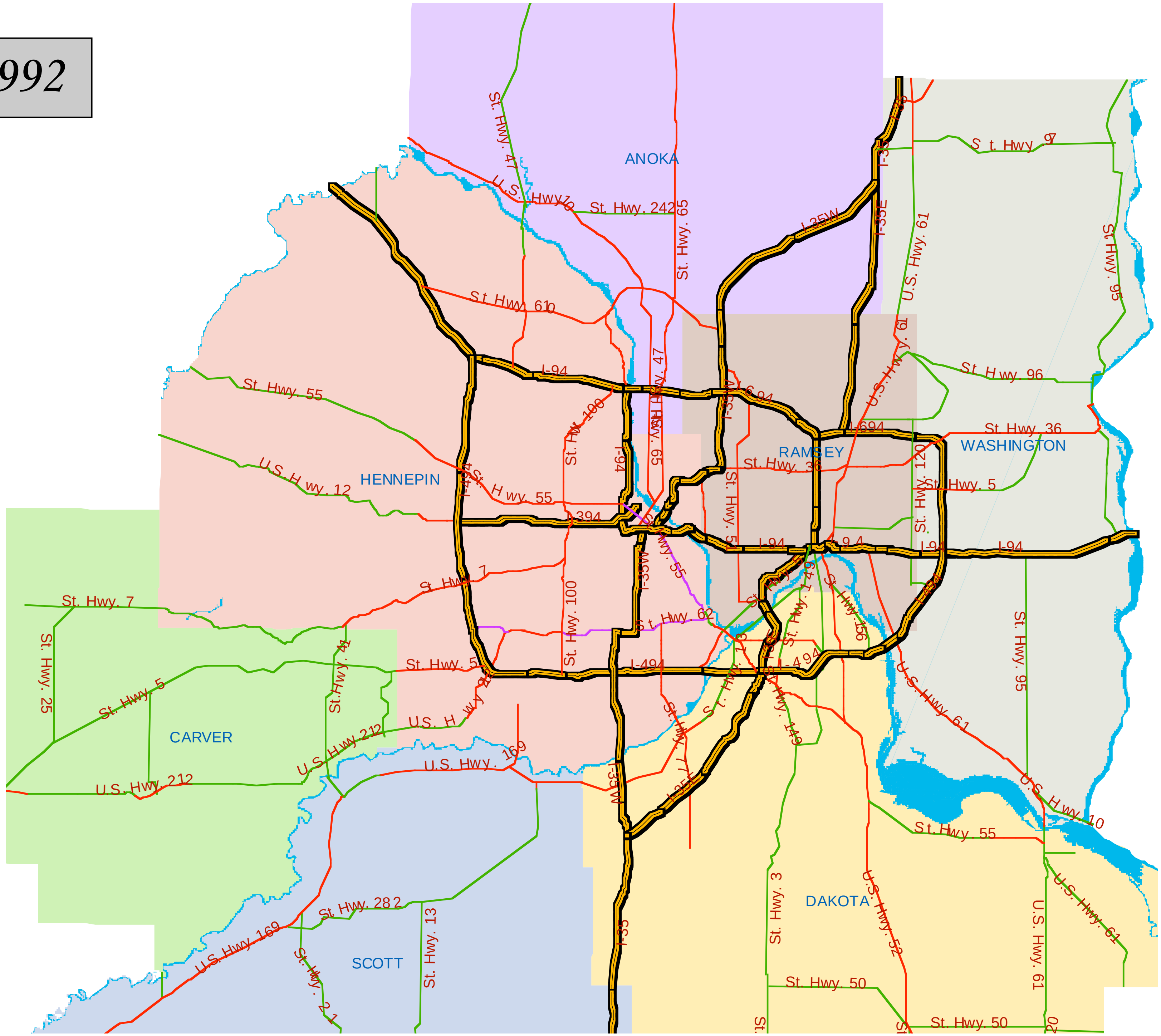

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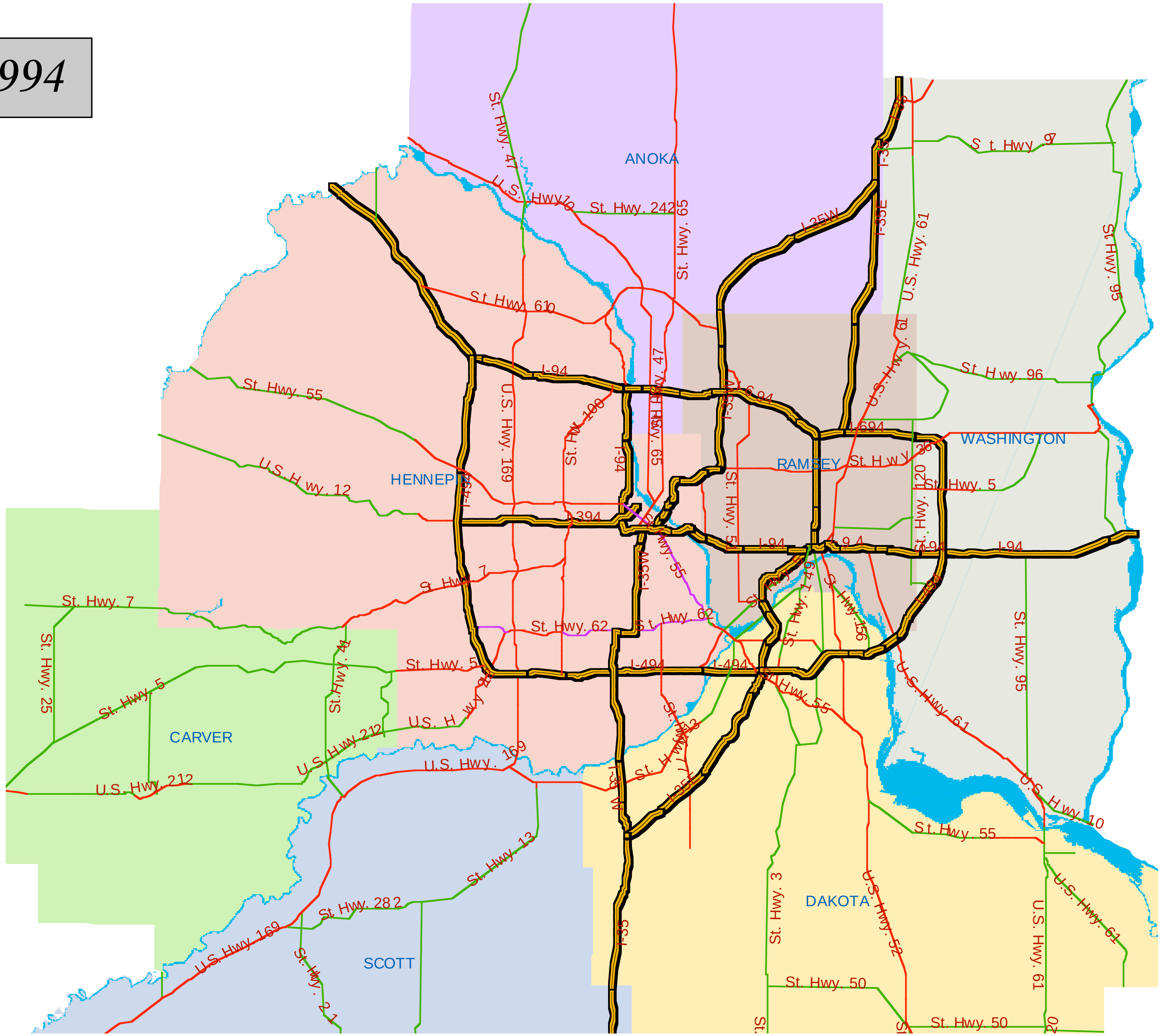
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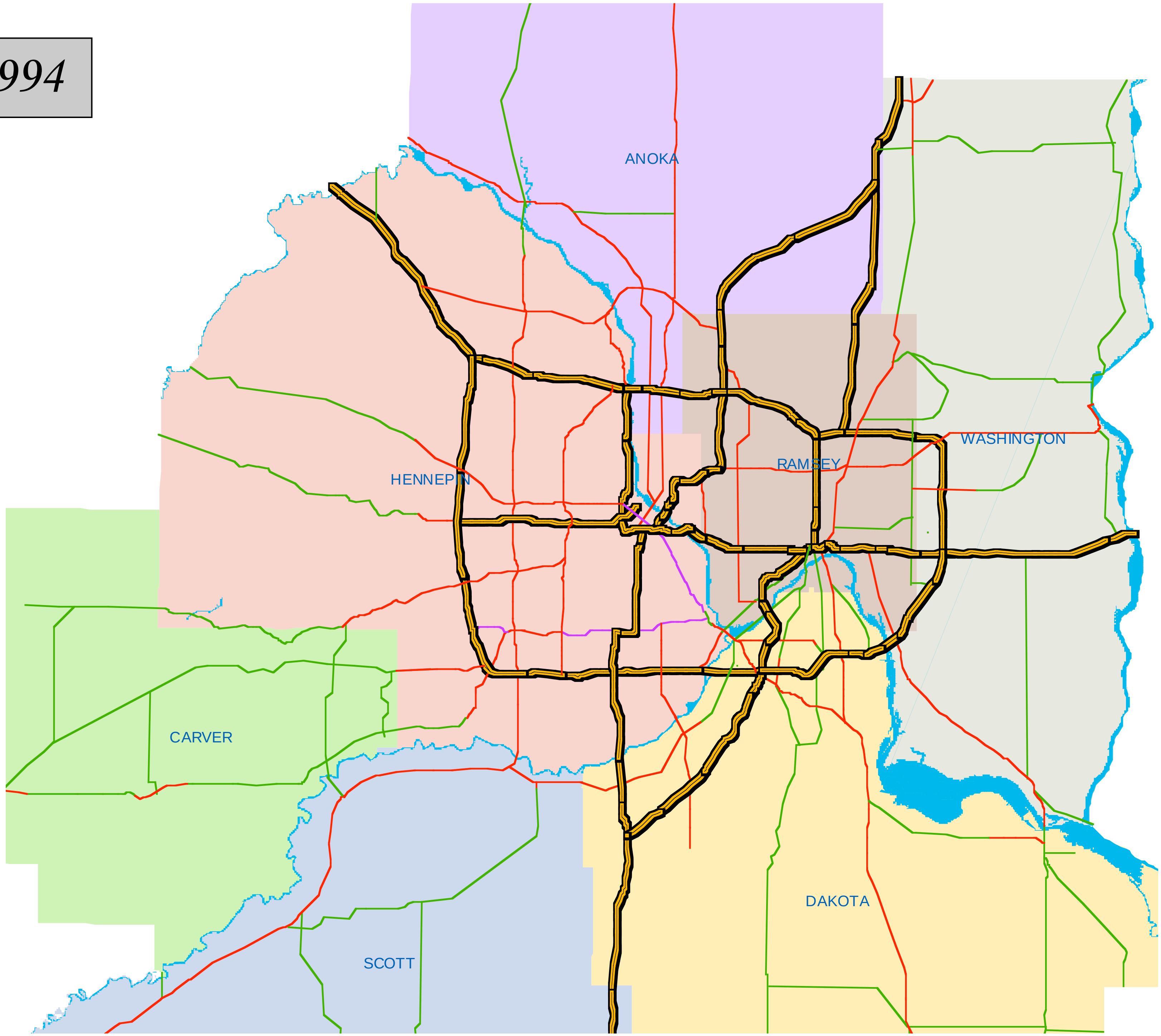

The Realm of Network Evolution

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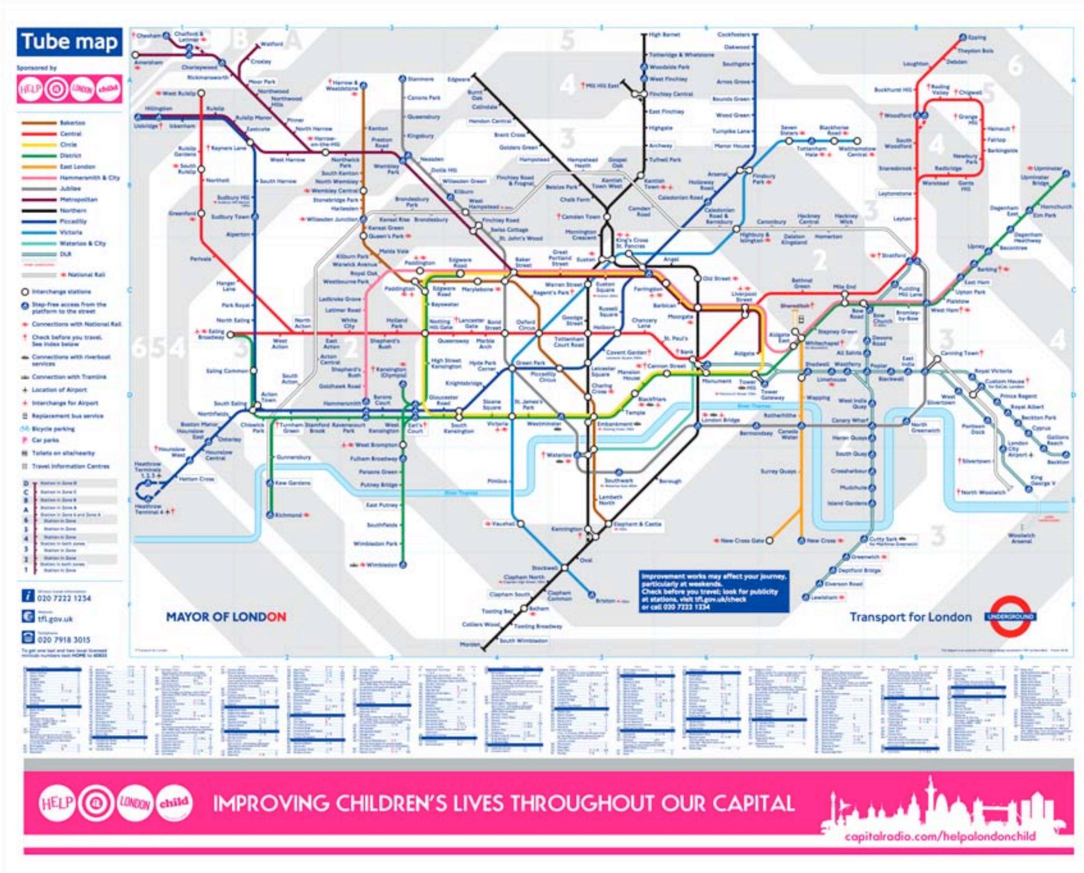
<tr><td colspan="3" rowspan="2">Tools: Statistical Estimation,
Agent-Based Simulation</td></tr>
<tr><td>Autonomous</td><td>Link - based</td></tr>
</table>

A Tale of Two Networks



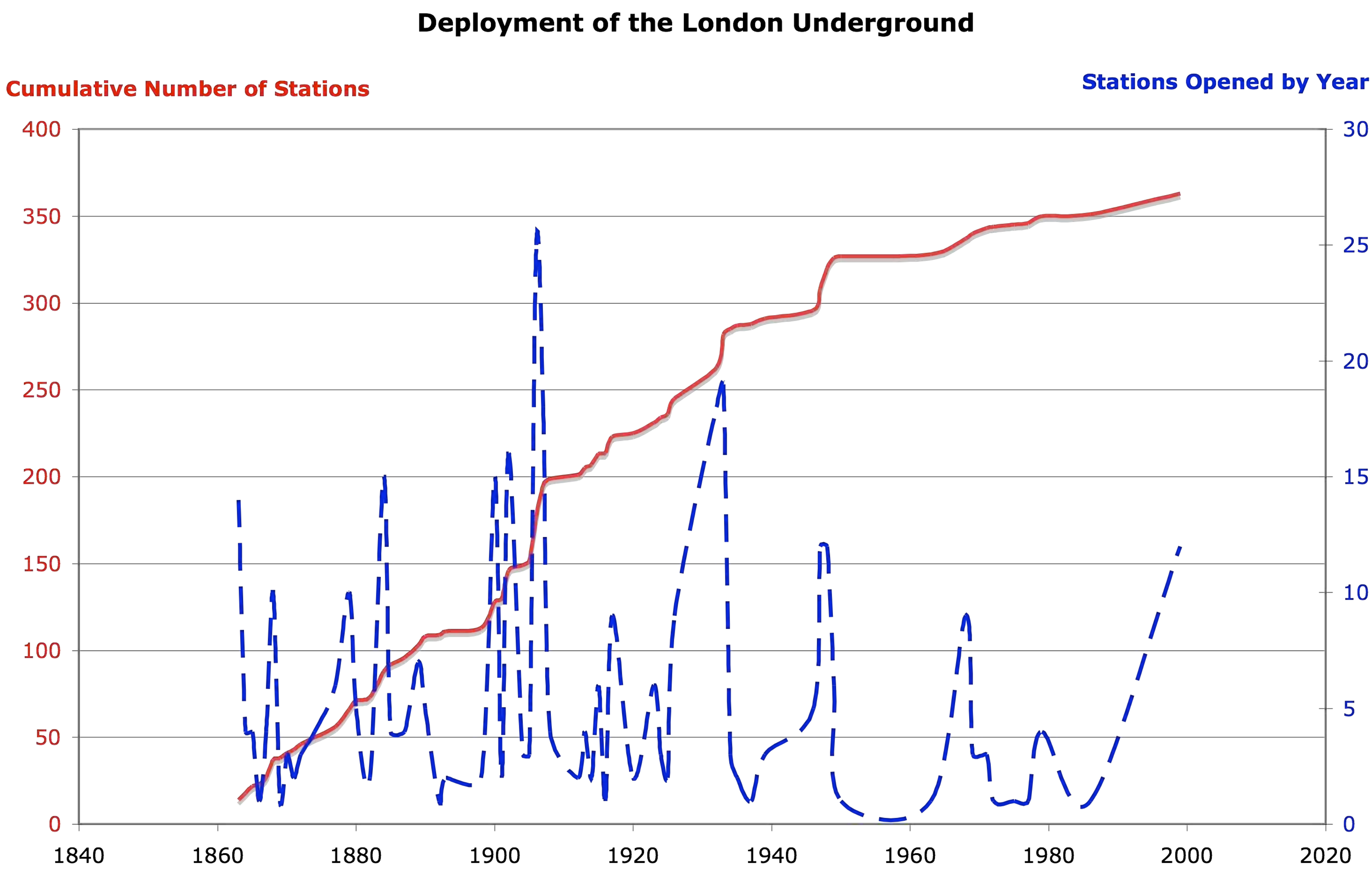
- It was the best of plans, it was the worst of plans …

Washington, DC

- Network (like city) planned as a whole, by a single (collective) agent in 1950s and 1960s, opened 1976
- Plans largely unchanged over 50 years despite changing circumstances
- 171 km, 564 k pax/day (out of Baltimore Washington metro pop of 8.5 m) [note also small Baltimore Metro)]

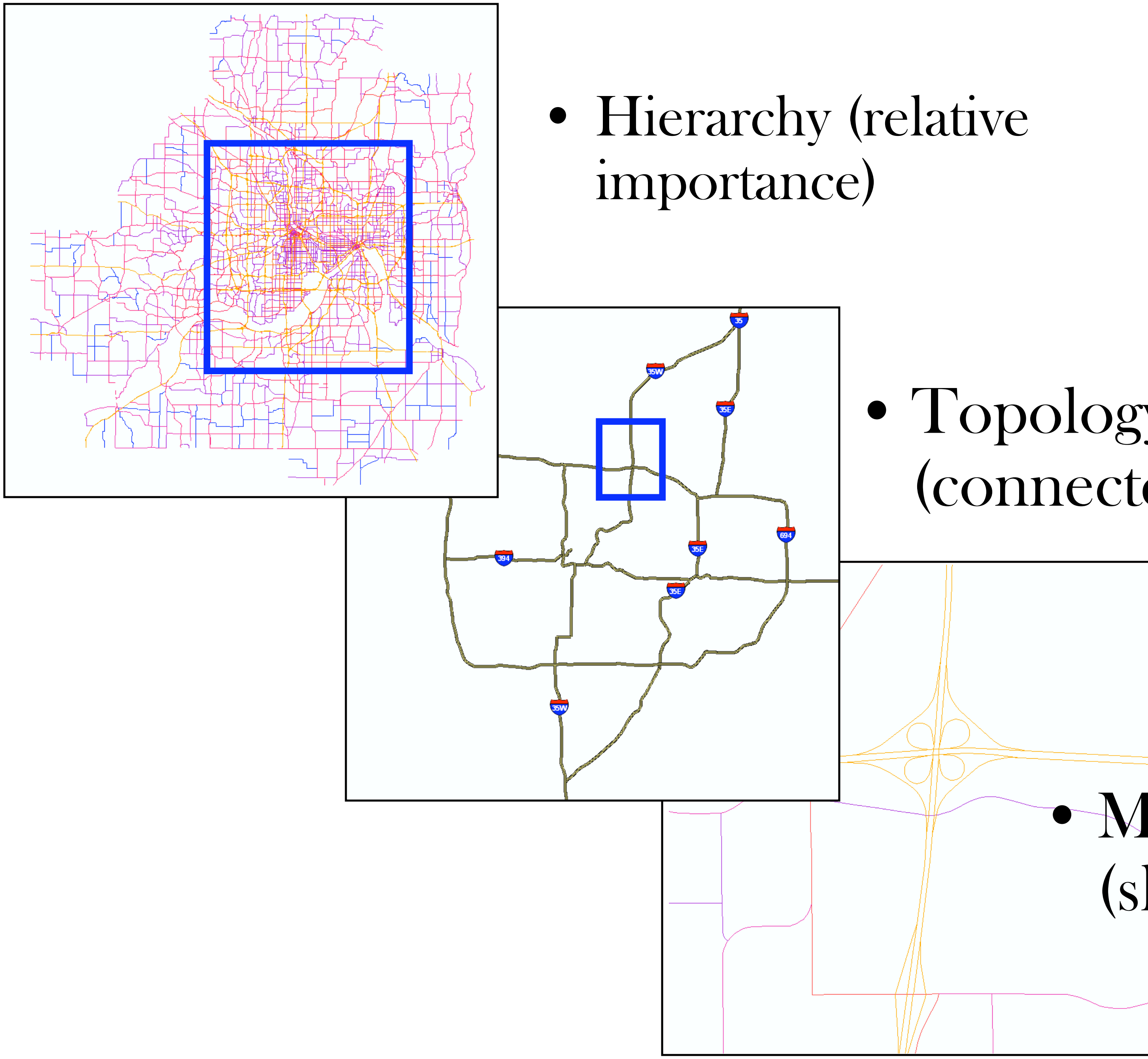
London, England

- Network "planned" by many independent agents (Metropolitan Line, District Line, Northern Line, etc.) over period from 1863 onwards
- Agents were consolidated over time, first by private sector (Charles Yerkes), then public sector (government)
- Private sector is being reintroduced using "PPP", private companies now responsible for infrastructure
- 408 km, 2.67 m pax/day (out of 7.5 m pop)

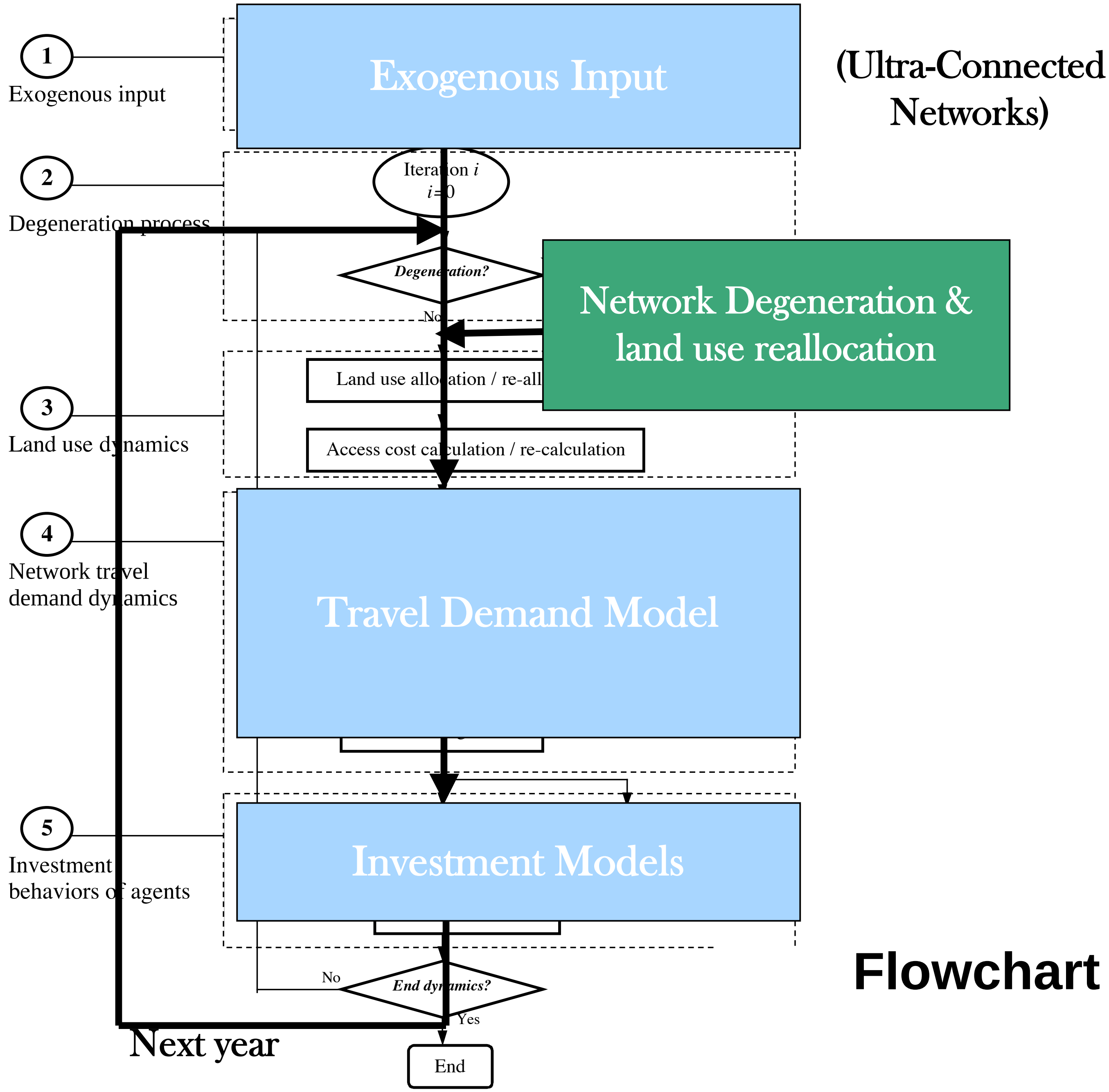

Deployment of the London Underground
Cumulative Number of Stations
Stations Opened by Year
400
350
300
250
200
150
100
50
0
30
25
20
15
10
5
0
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020

Network Growth Occurs Over Space and Time

- Economics historically (since Classical period anyway) was inured to space and time, assumed perfect information, and dealt with population aggregates
- Need to take different approaches: agent-based, taking place over space and time, with imperfect information, and heuristics



- Hierarchy (relative importance)
- Topology (connectedness)
- Morphology (shape)


(Ultra-Connected Networks)
1
Exogenous input
Exogenous Input
2
Degeneration process
Iteration i
i=0
Degeneration?
No
Network Degeneration & land use reallocation
3
Land use dynamics
Land use allocation / re-all
Access cost calculation / re-calculation
4
Network travel demand dynamics
Travel Demand Model
5
Investment behaviors of agents
Investment Models
No
End dynamics?
Yes
Next year
End
Flowchart

Revenue And Cost Models

- Toll is the only source of revenue
- Annual revenue generated by a link is total toll paid by the travelers

$$\tau_a = \rho_0 l_a^{\rho_1} v_a^{\rho_2}$$

$$R_a = \tau_a (365 \cdot f_a)$$

- Initially assume only one type of cost, function of length, flow, link speed

$$C_a = \mu \cdot l_a^{\alpha_1} \cdot f_a^{\alpha_2} \cdot v_a^{\alpha_3}$$

Network Investment Model (1)

- A link based model
- Speed of a link improves if revenue is more than cost of maintenance, drops otherwise

$$v_a^{t+1} = v_a^t \left(\frac{R_a}{C_a} \right)^{\beta}$$

Where:

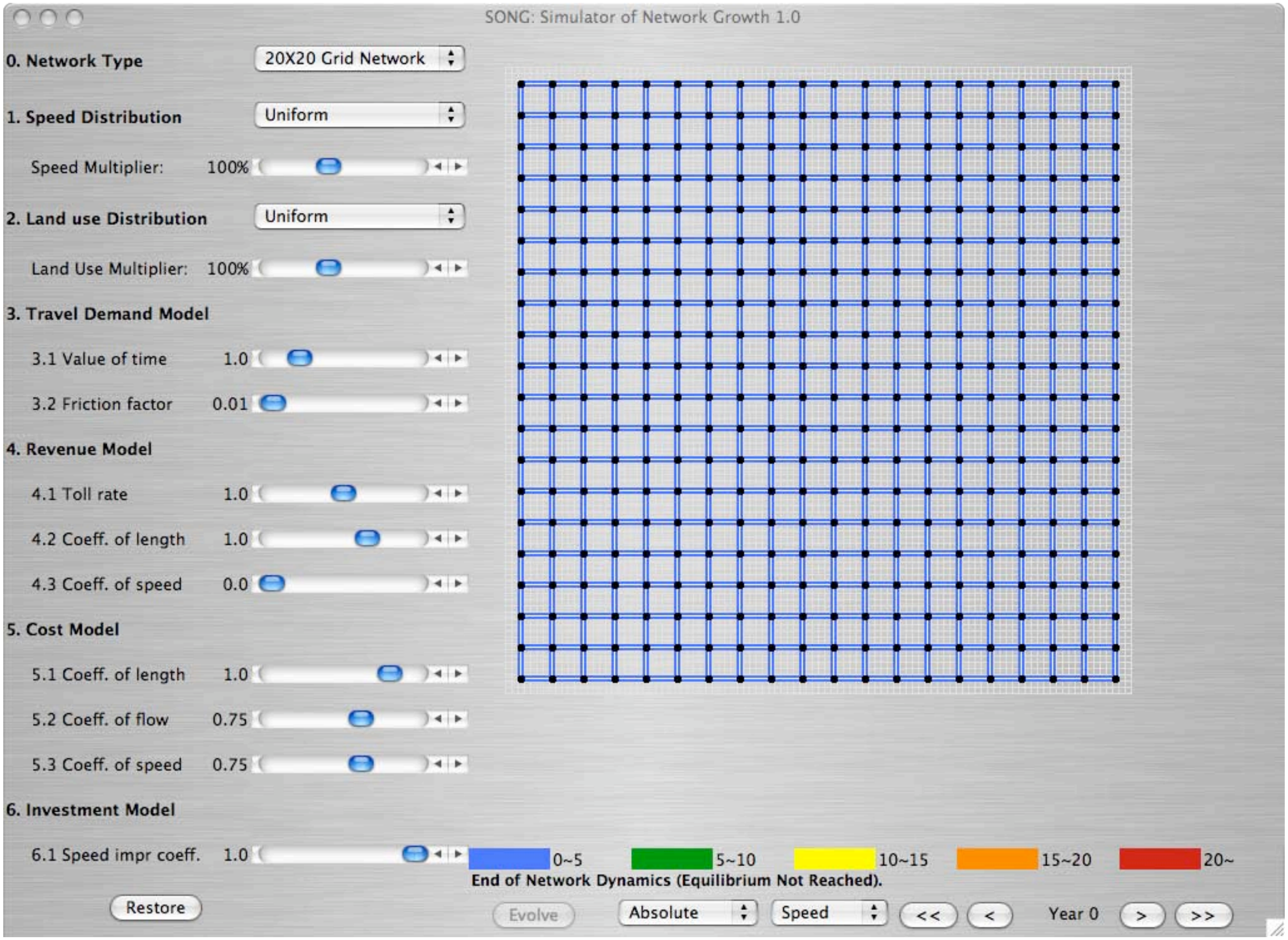
v_a^t is speed of link *a* at time step *t*,

β is speed reduction coefficient.

No revenue sharing between links: Revenue from a link is used in its own investment

Initial Assumptions

- Base case
  - Network - speed ~ U(1, 1)
  - Land use ~ U(10, 10)
  - Friction factor w=0.01
  - Travel cost, Revenue d_a $\{\lambda = 1.0, \rho_o = 1.0, \rho_1 = 1.0, \rho_2 = 0.0\}$
  - Infrastructure Cost $\{\mu = 365, \alpha_1 = 1.0, \alpha_2 = 0.75, \alpha_3 = 0.75\}$
  - Investment model $\{\beta = 1.0\}$
  - Speeds on links running in opposite direction between same nodes are averaged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Uniform
Speed Multiplier:
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2. Land use Distribution
Uniform
Land Use Multiplier:
100%
3. Travel Demand Model
3.1 Value of time
1.0
3.2 Friction factor
0.01
4. Revenue Model
4.1 Toll rate
1.0
4.2 Coeff. of length
1.0
4.3 Coeff. of speed
0.0
5. Cost Model
5.1 Coeff. of length
1.0
5.2 Coeff. of flow
0.75
5.3 Coeff. of speed
0.75
6. Investment Model
6.1 Speed impr coeff.
1.0
Restore
0~5
5~10
10~15
15~20
20~
End of Network Dynamics (Equilibrium Not Reached).
Evolve
Absolute
Speed
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Year 0
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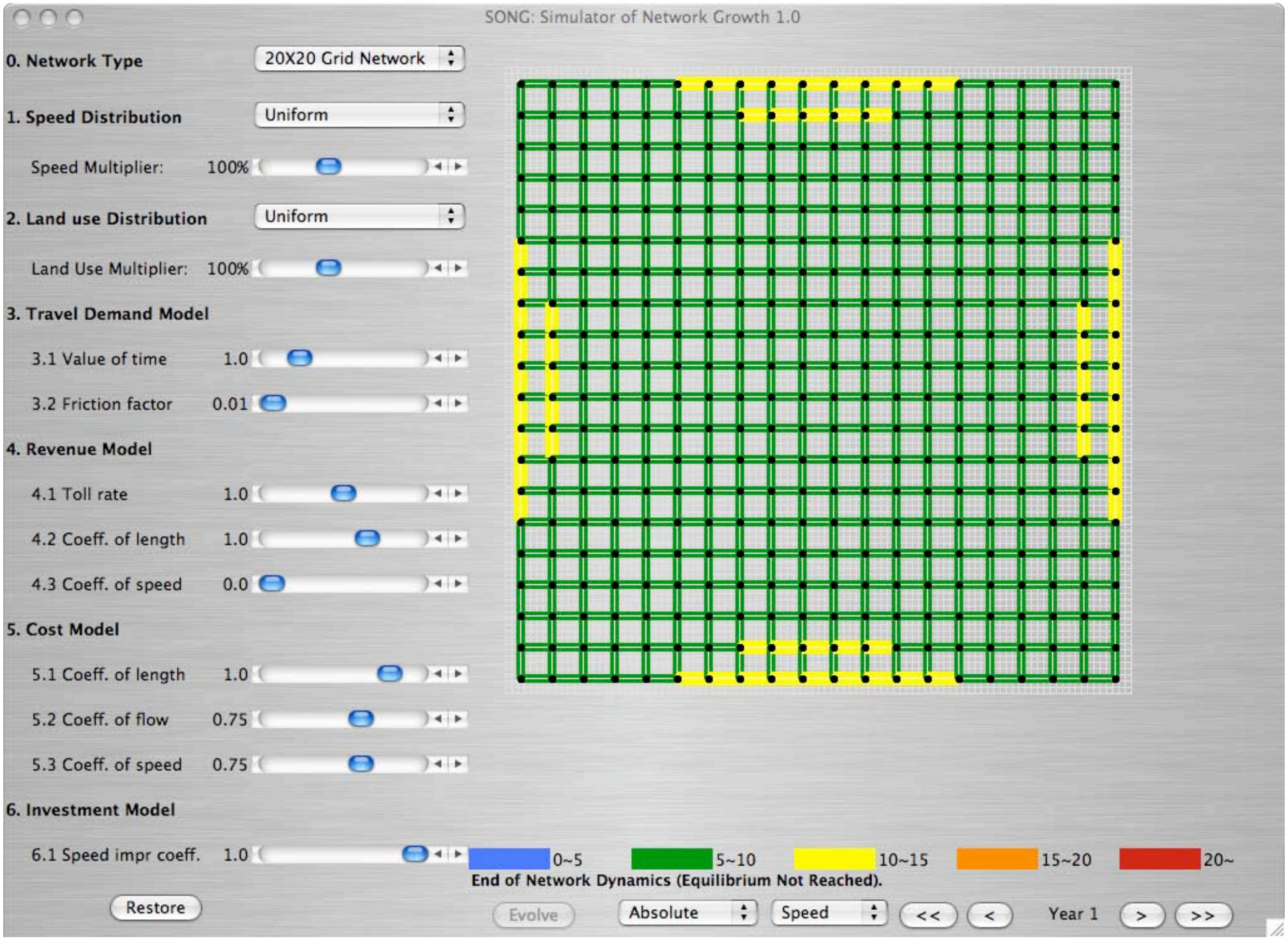
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5.3 Coeff. of speed 0.75
6. Investment Model
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Restore
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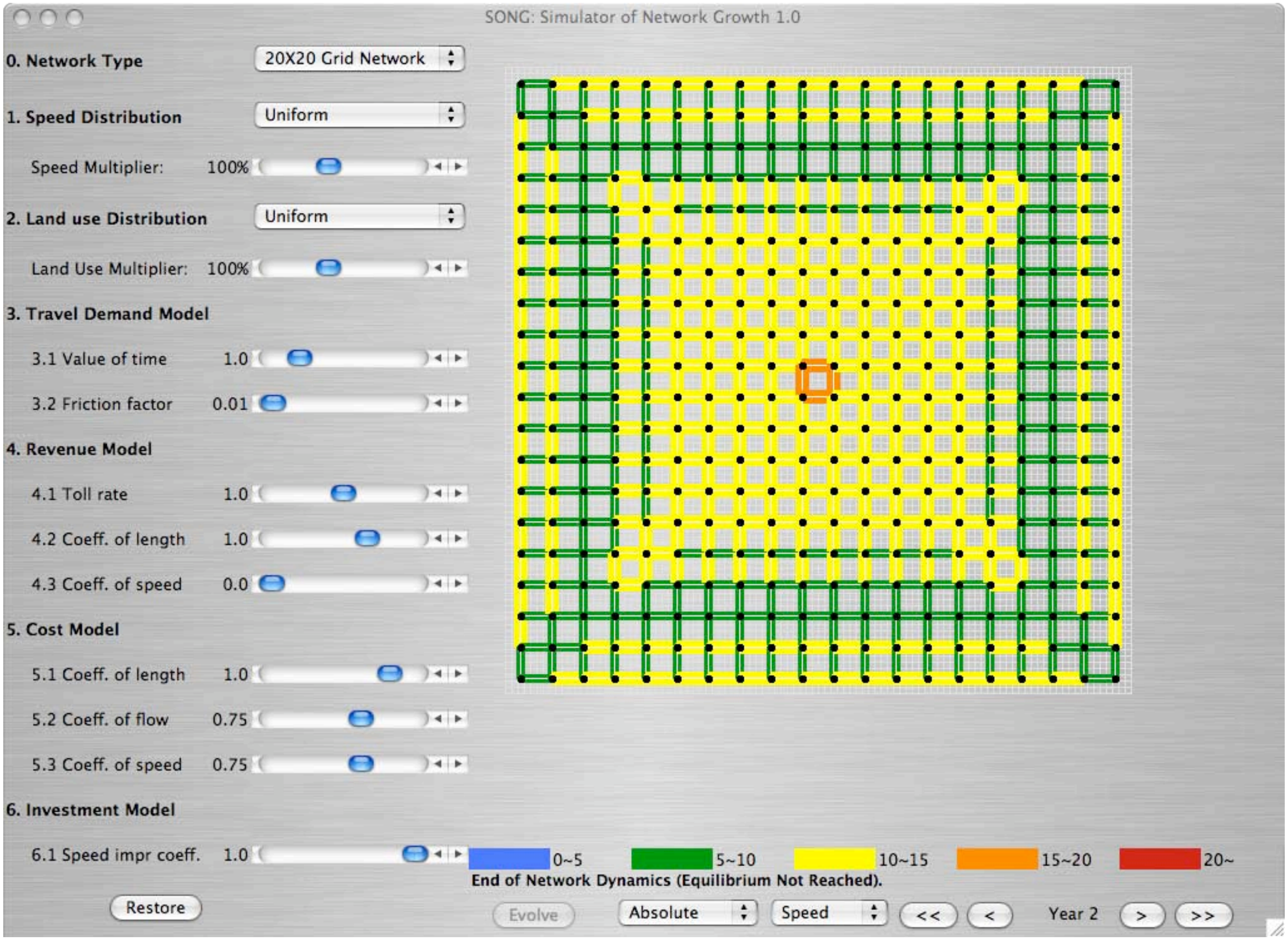
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5.3 Coeff. of speed 0.75
6. Investment Model
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Restore
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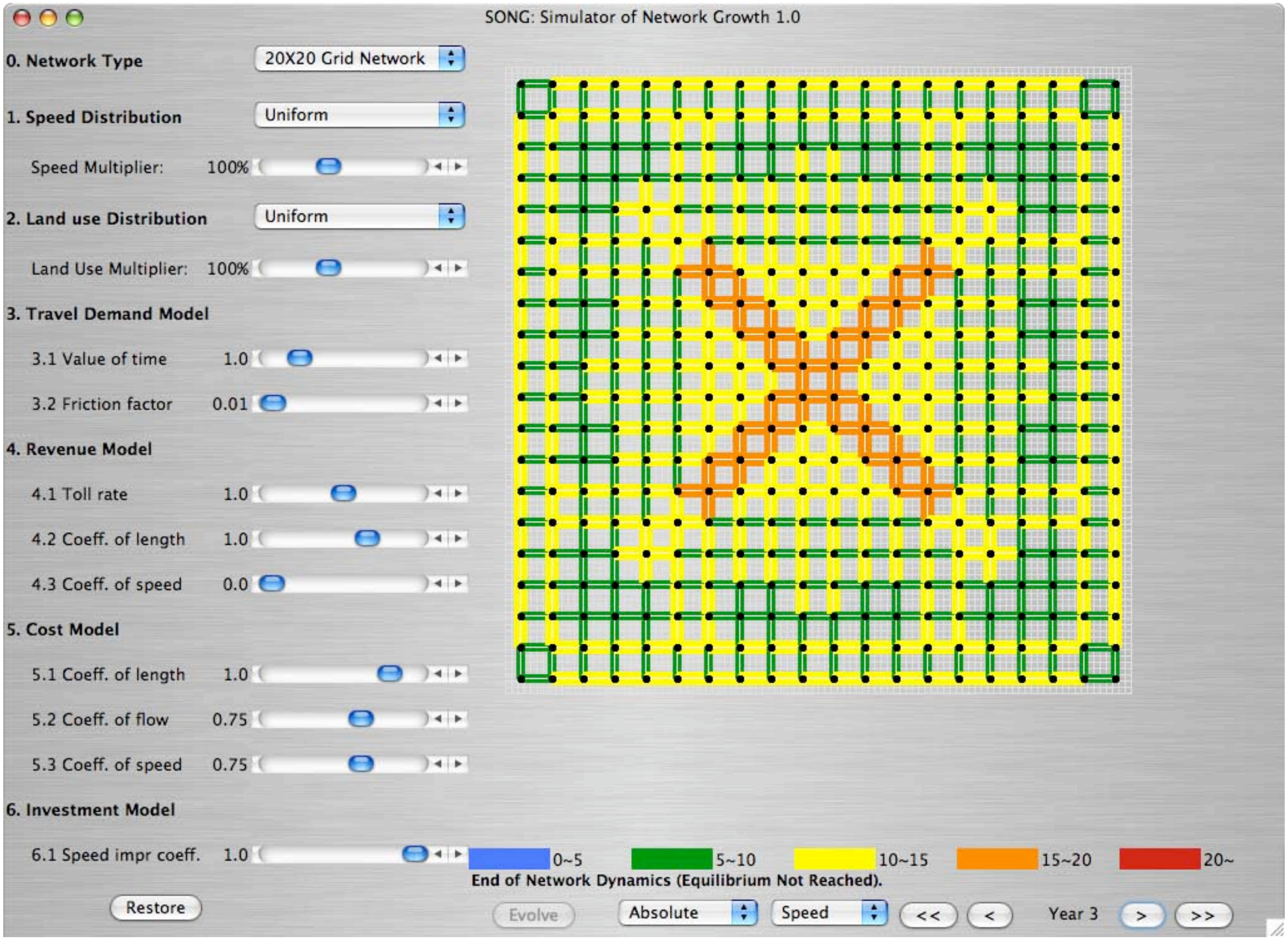
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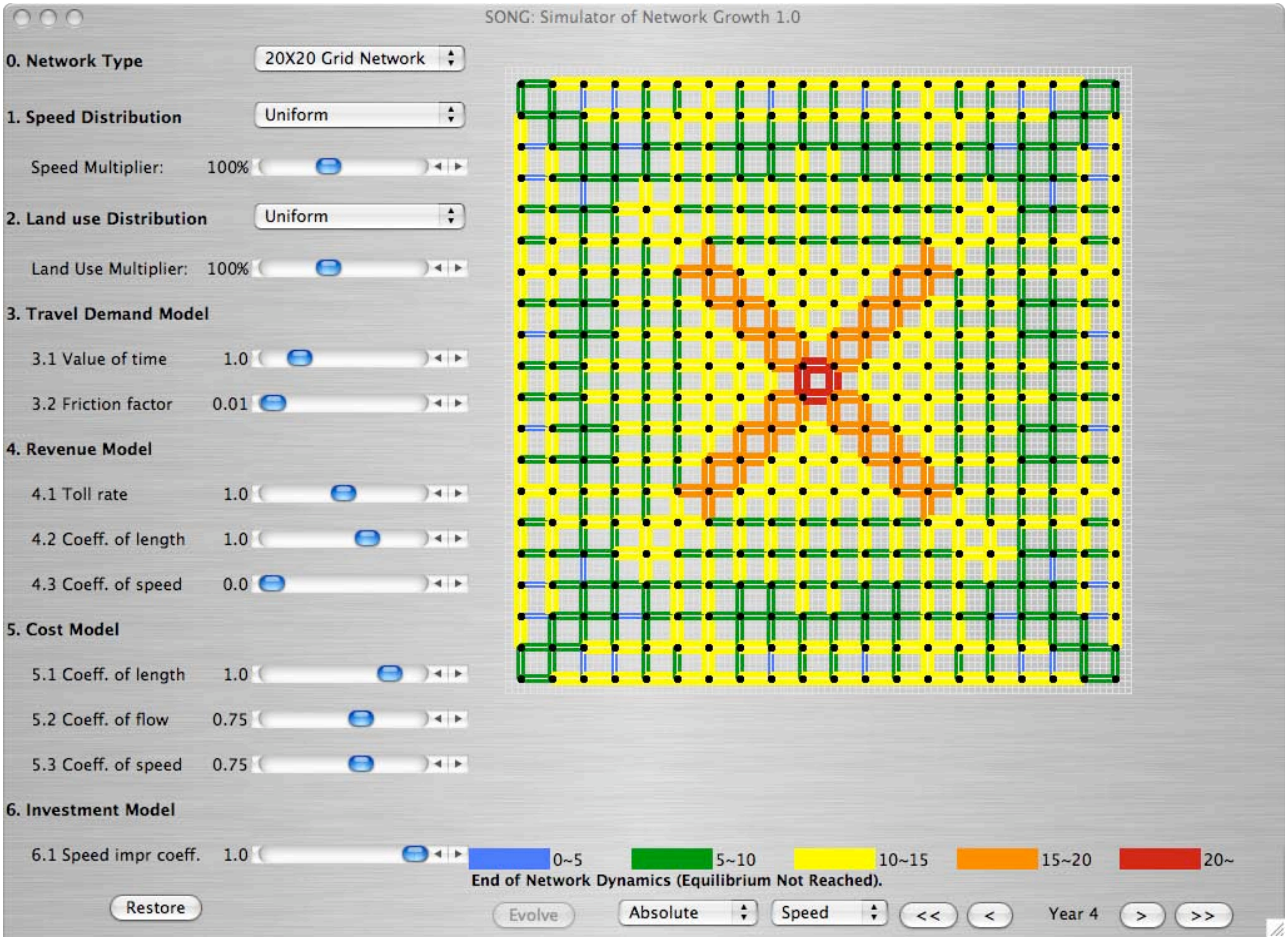
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5.3 Coeff. of speed 0.75
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Evolve
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Speed
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Year 4
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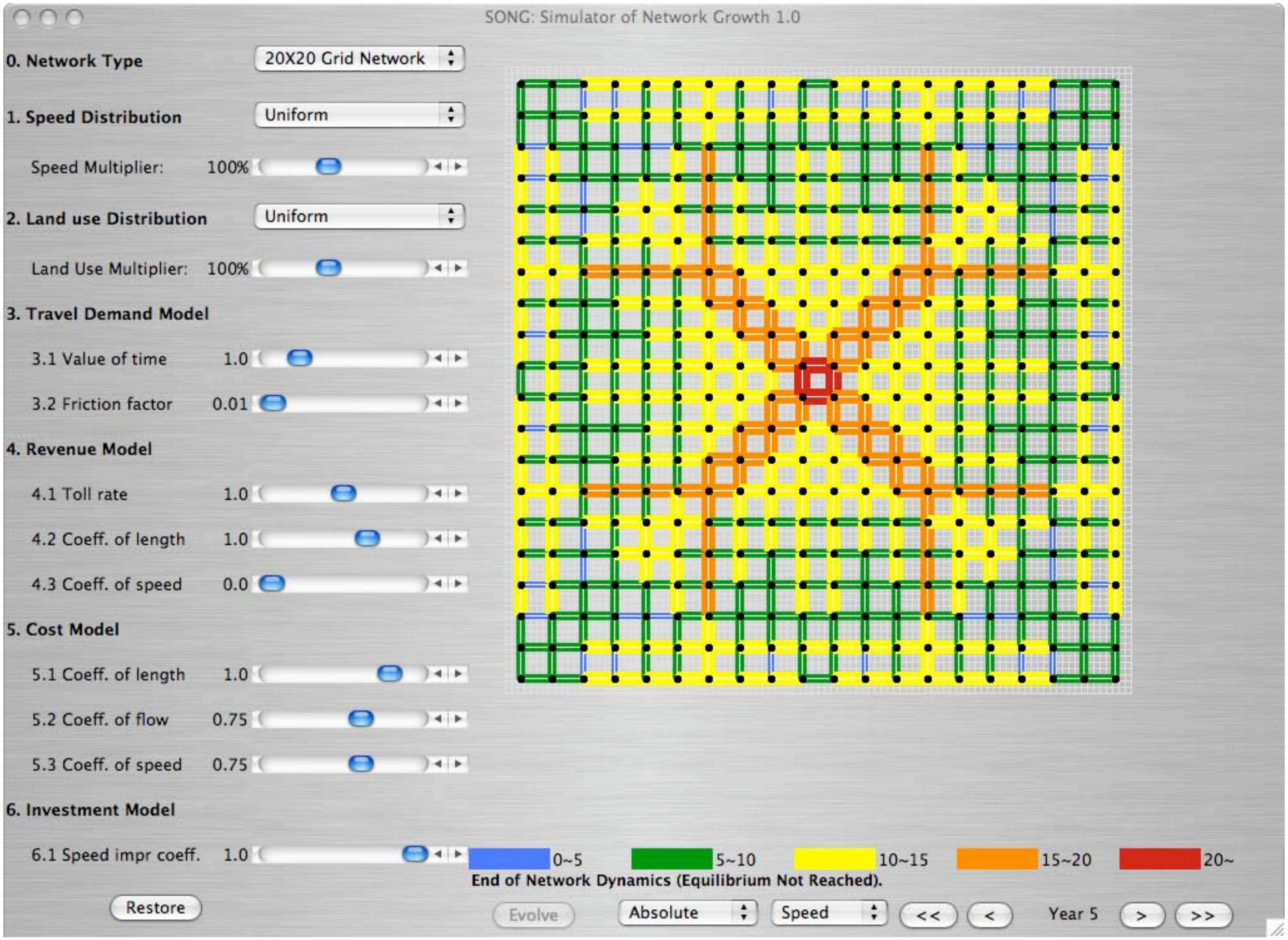
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Speed
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Year 5
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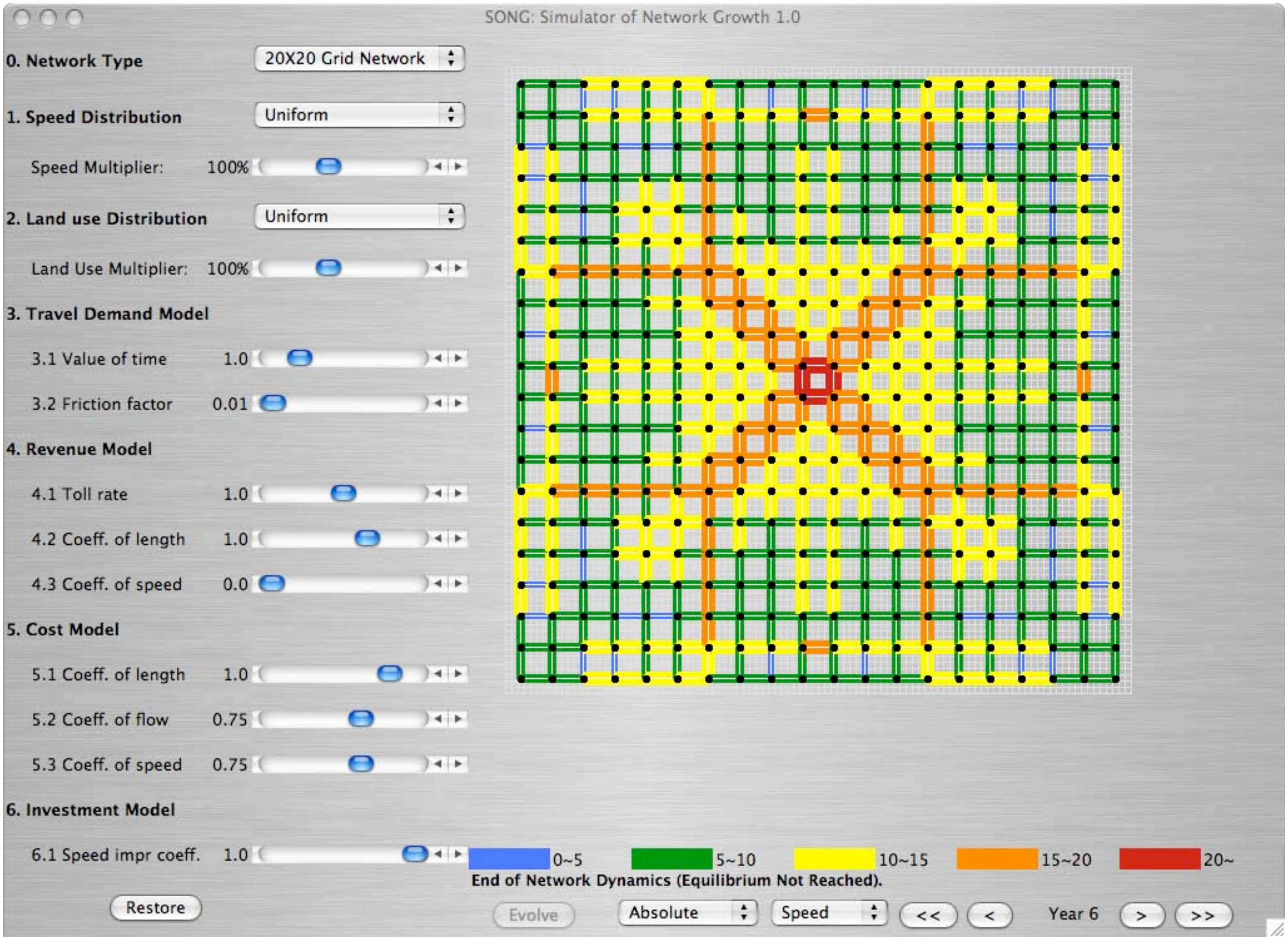

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Evolve
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Speed
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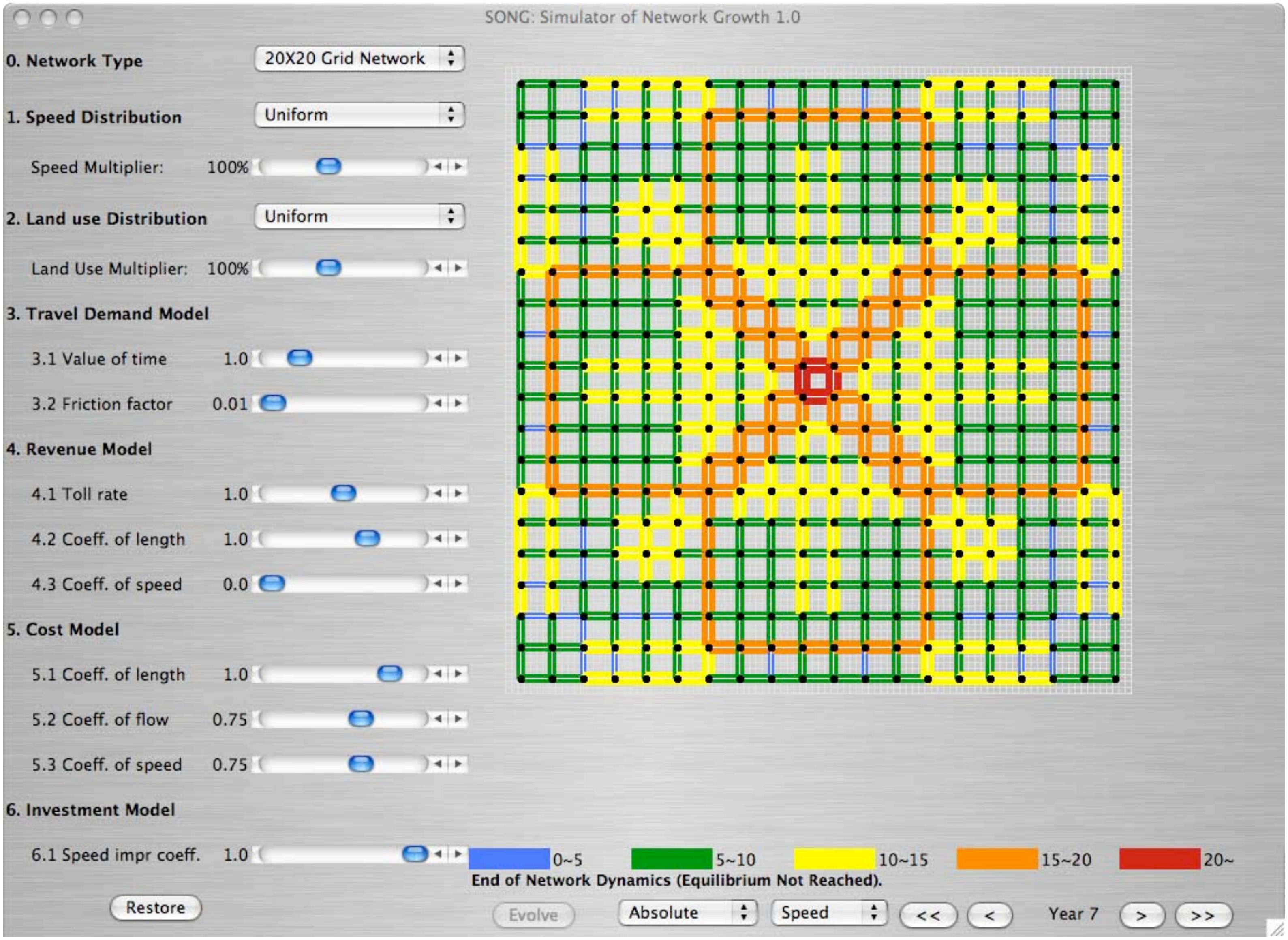
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Evolve
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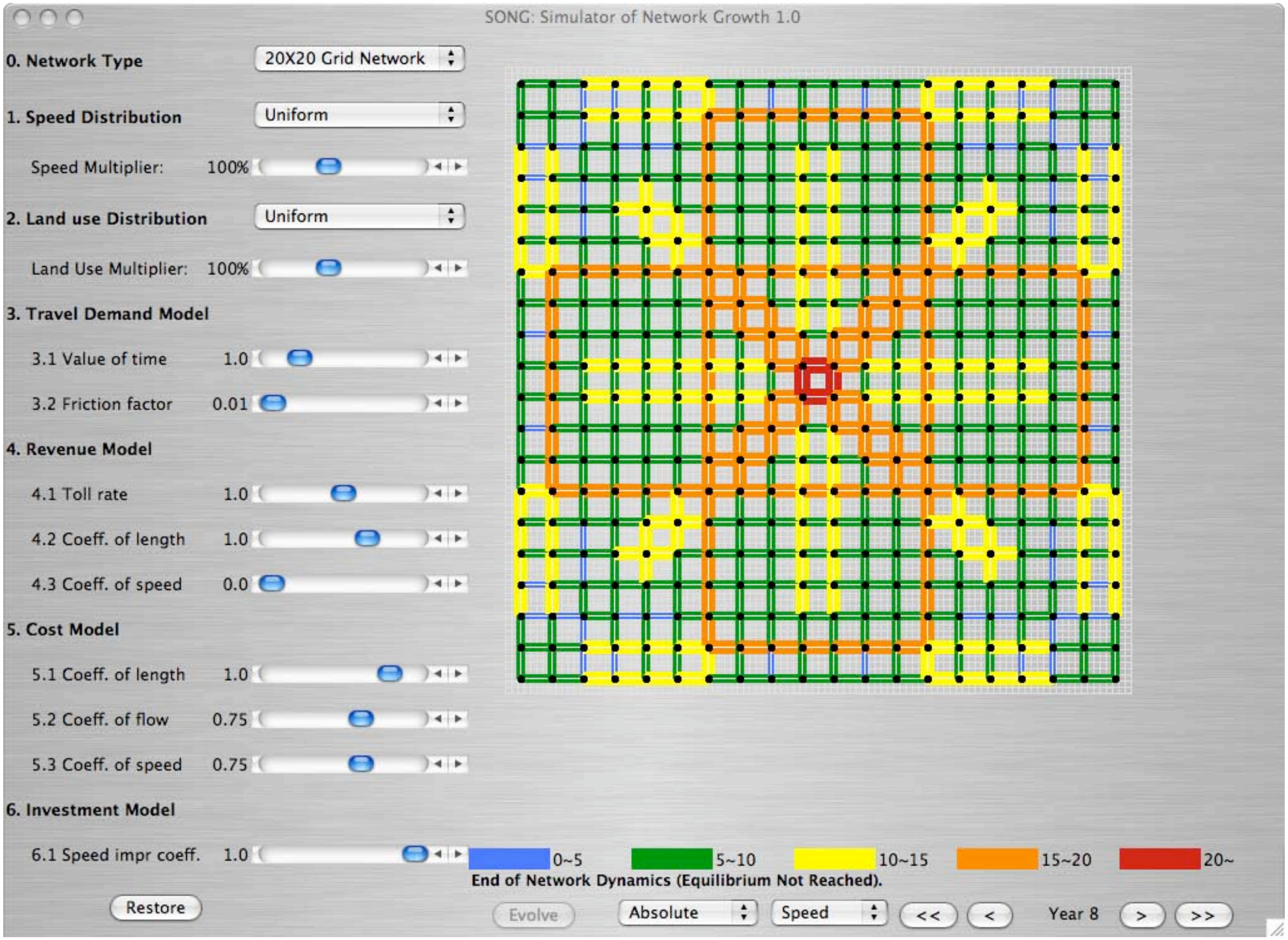
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Evolve
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Year 8
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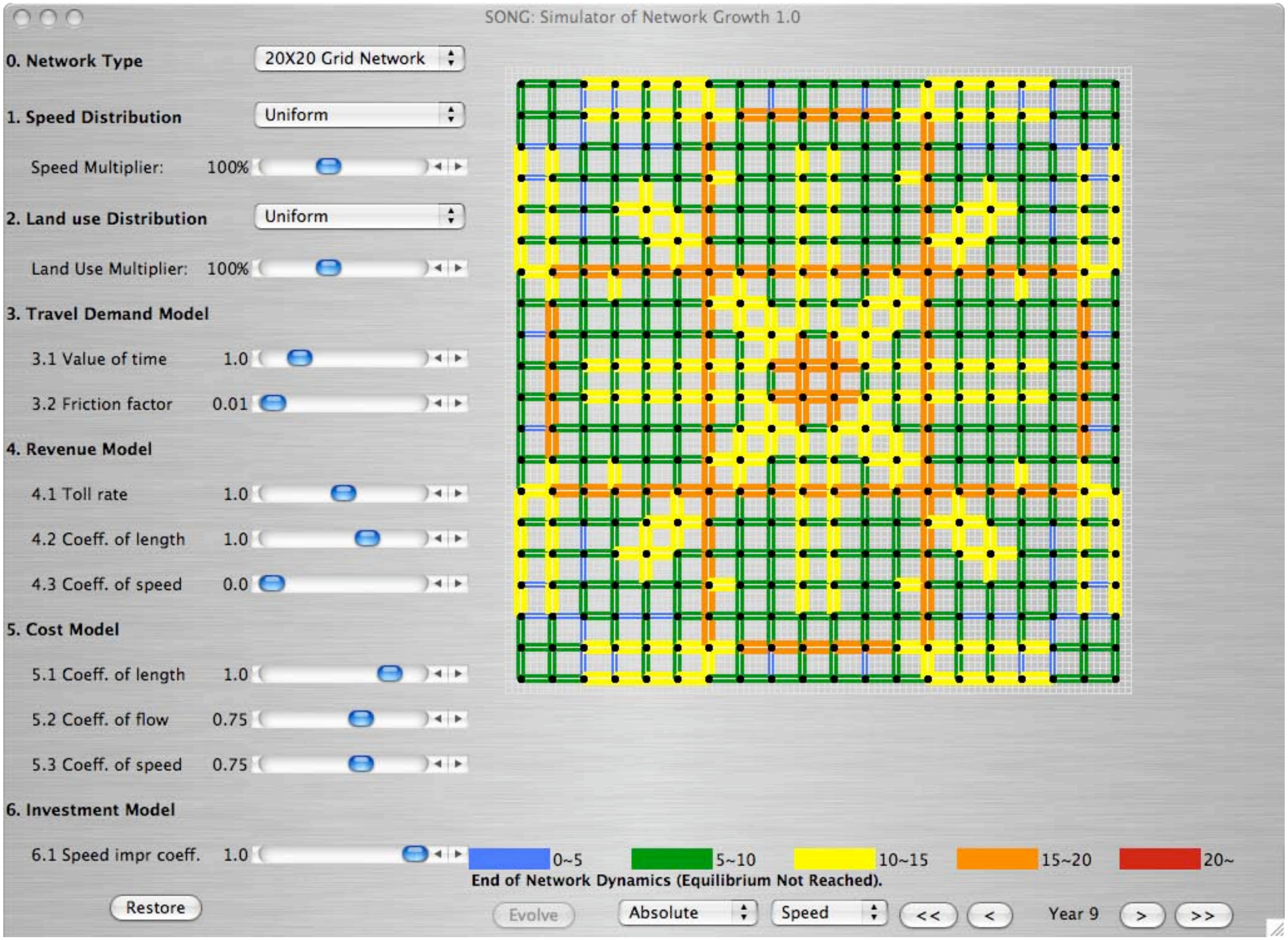
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5.3 Coeff. of speed 0.75
6. Investment Model
6.1 Speed impr coeff. 1.0
Restore
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End of Network Dynamics (Equilibrium Not Reached).
Evolve
Absolute
Speed
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Year 9
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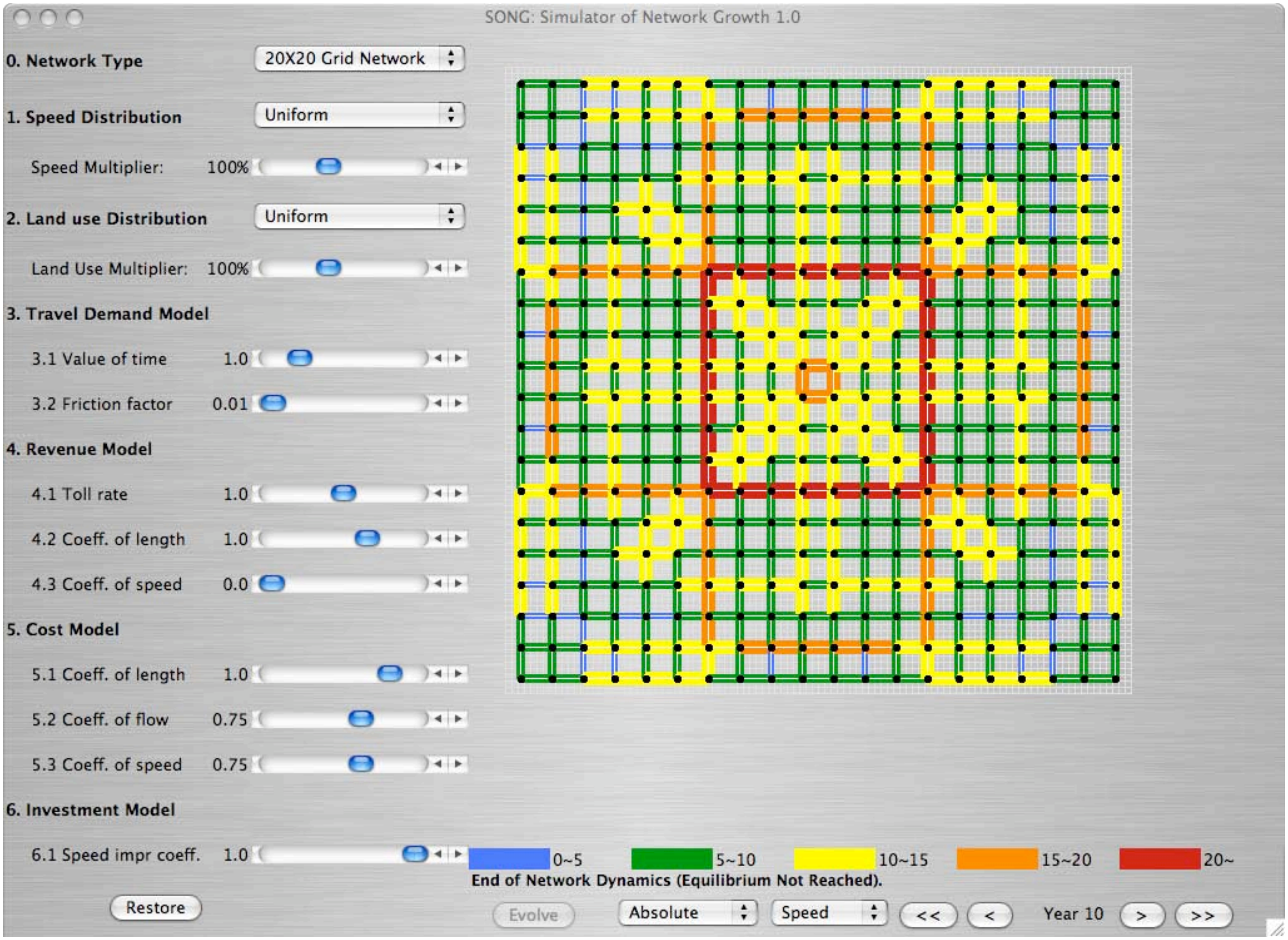
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Evolve
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Speed
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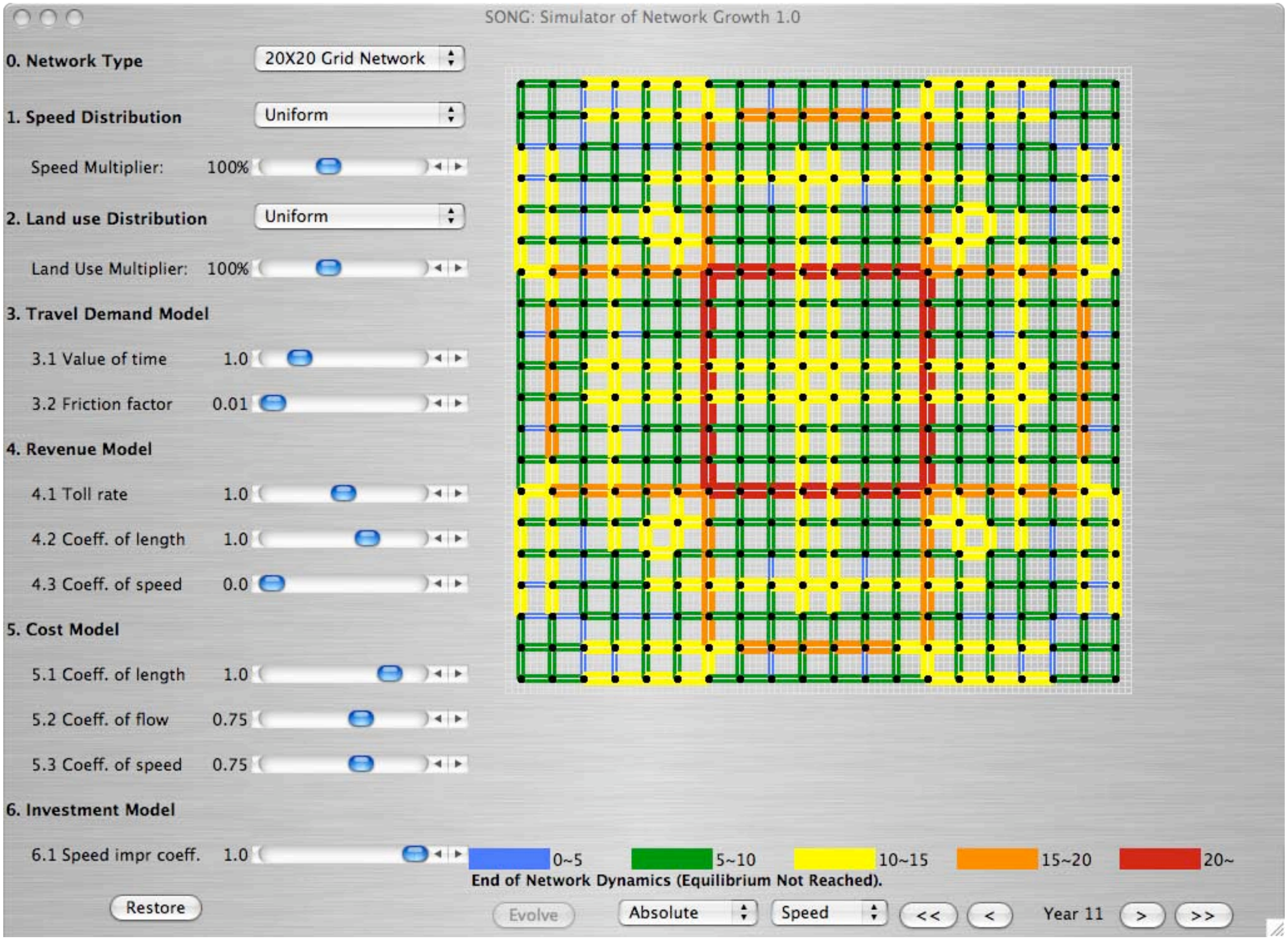
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Evolve
Absolute
Speed
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Year 11
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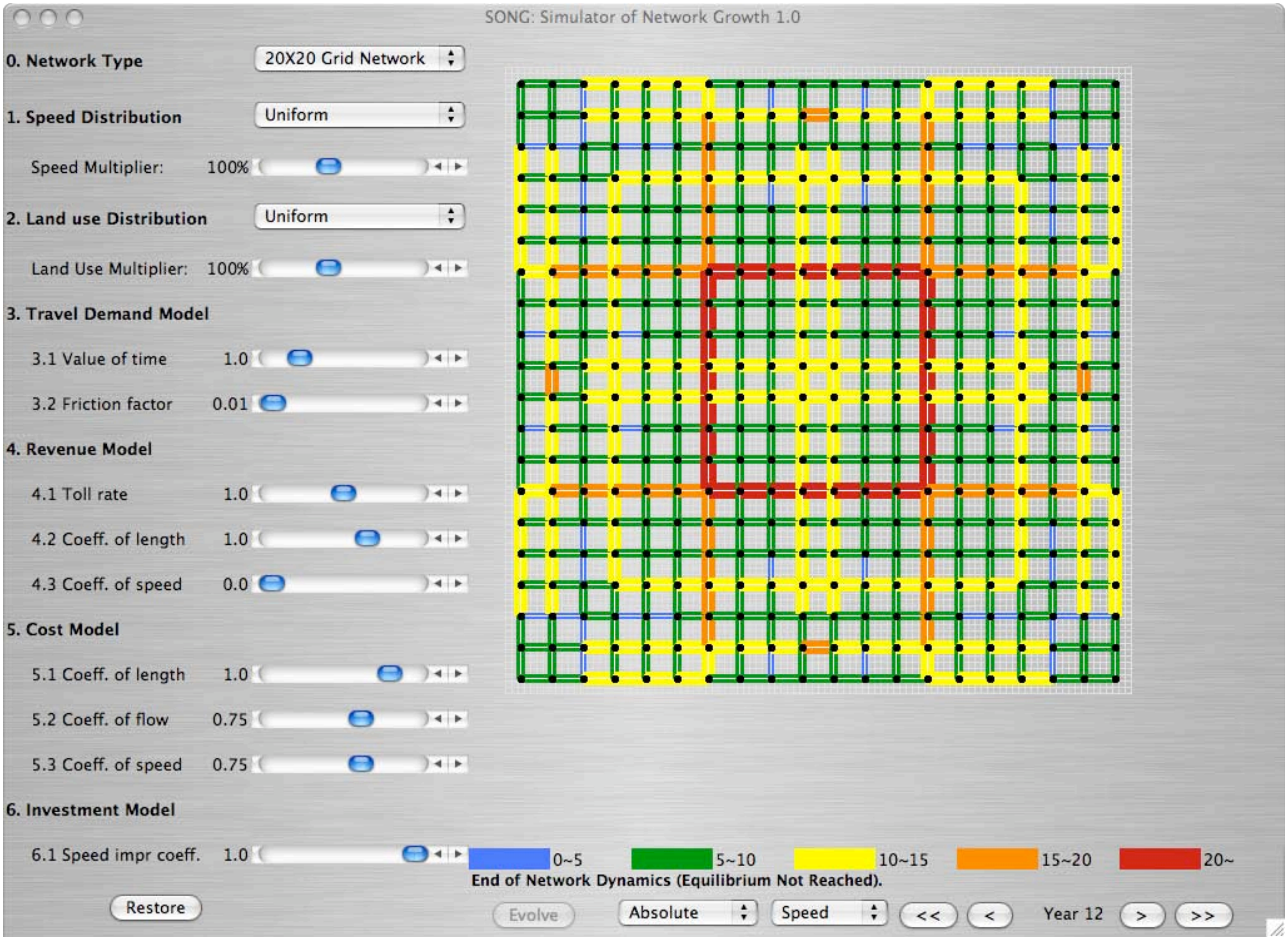
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Evolve
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Speed
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Year 12
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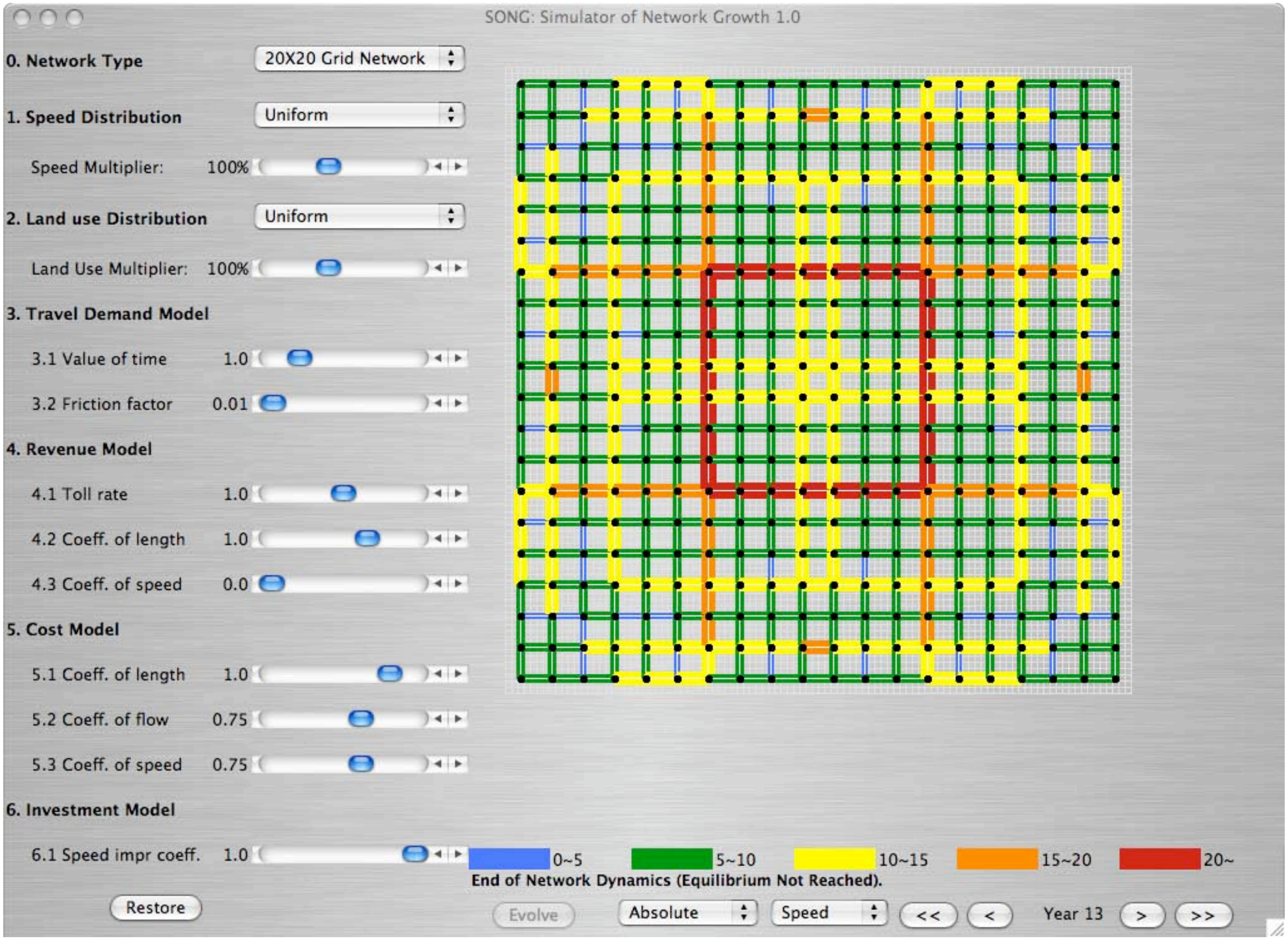
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Evolve
Absolute
Speed
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Year 13
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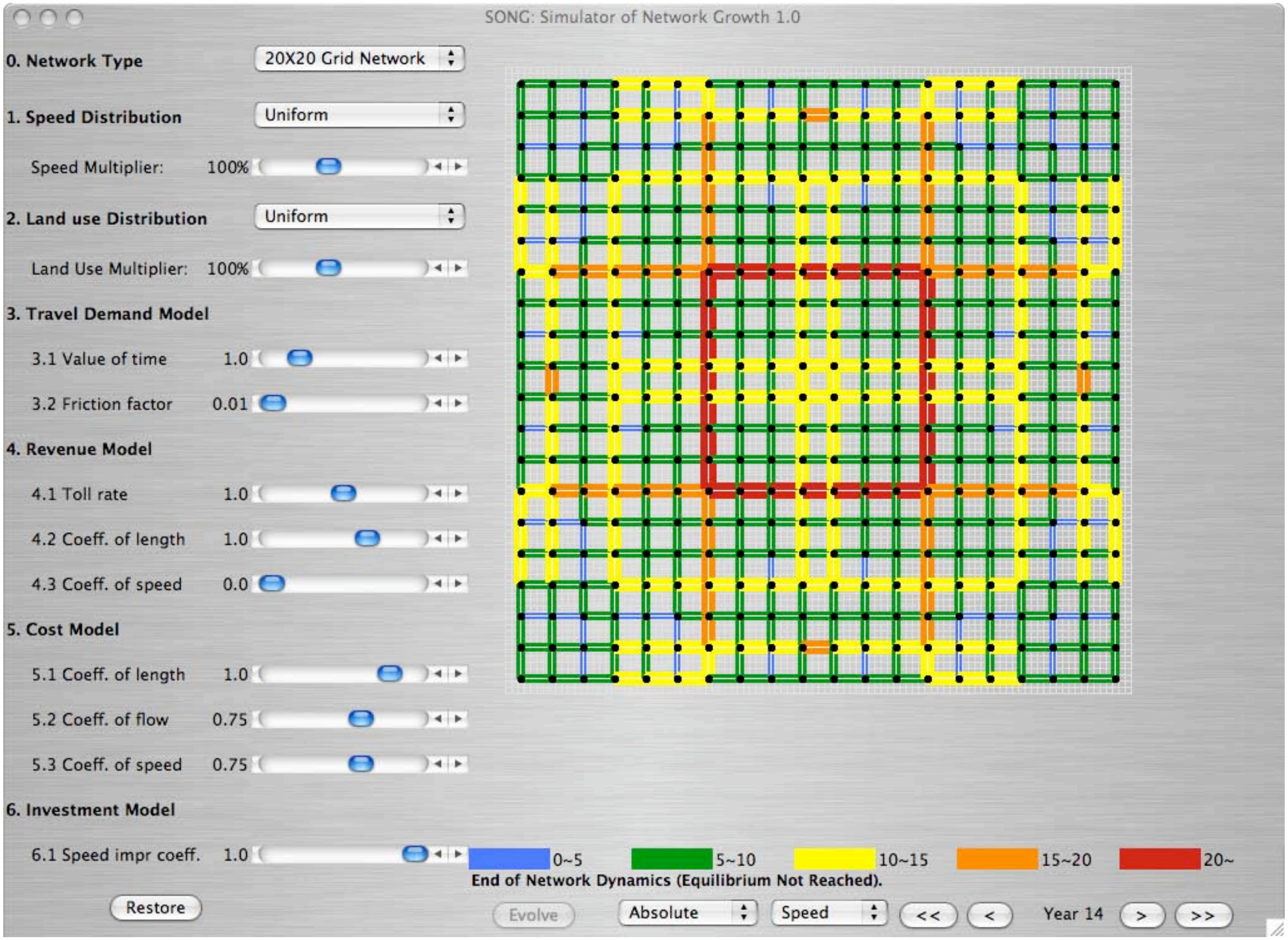
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Evolve
Absolute
Speed
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Year 14
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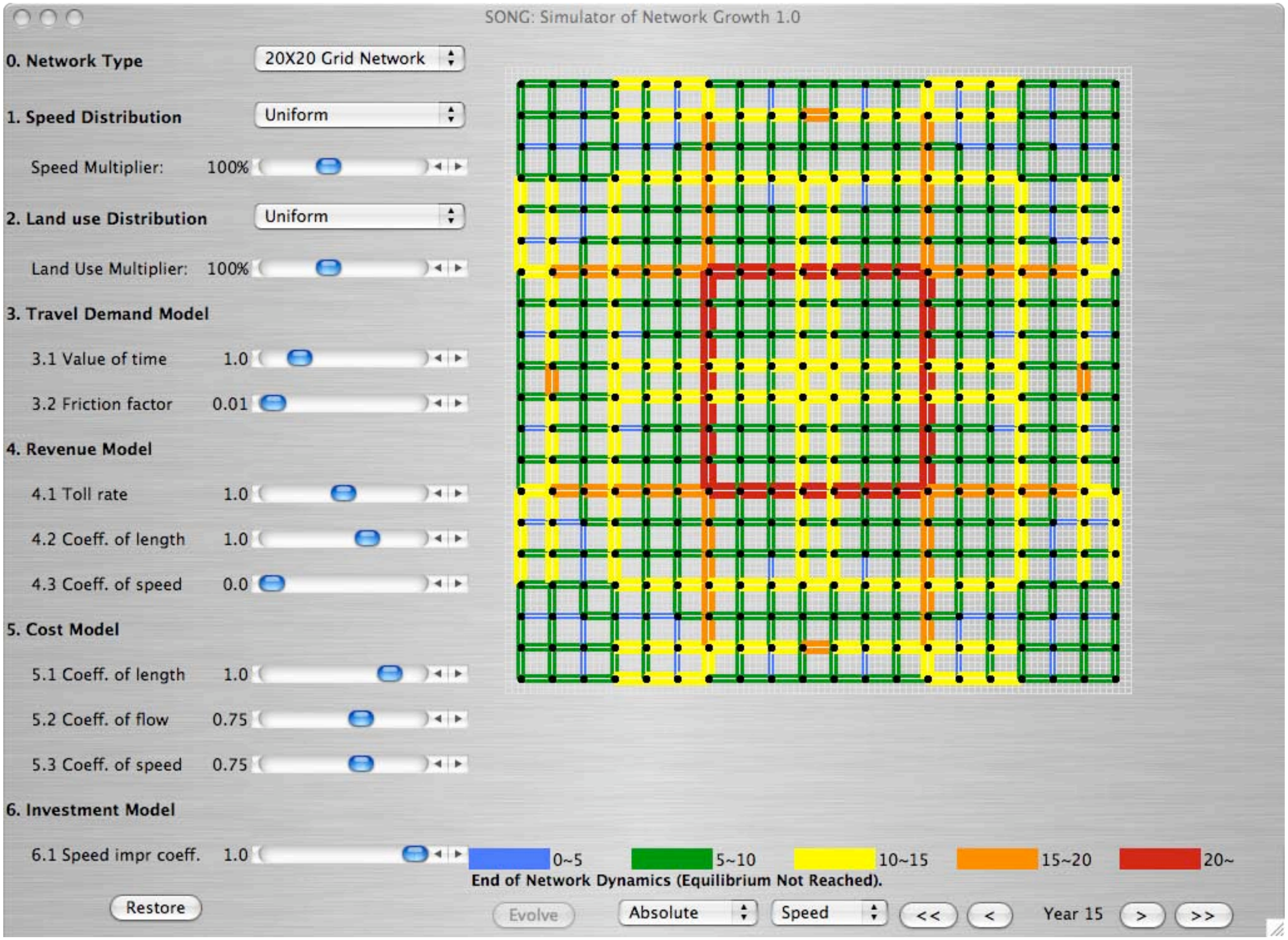
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Restore
0~5
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20~
End of Network Dynamics (Equilibrium Not Reached).
Evolve
Absolute
Speed
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Year 15
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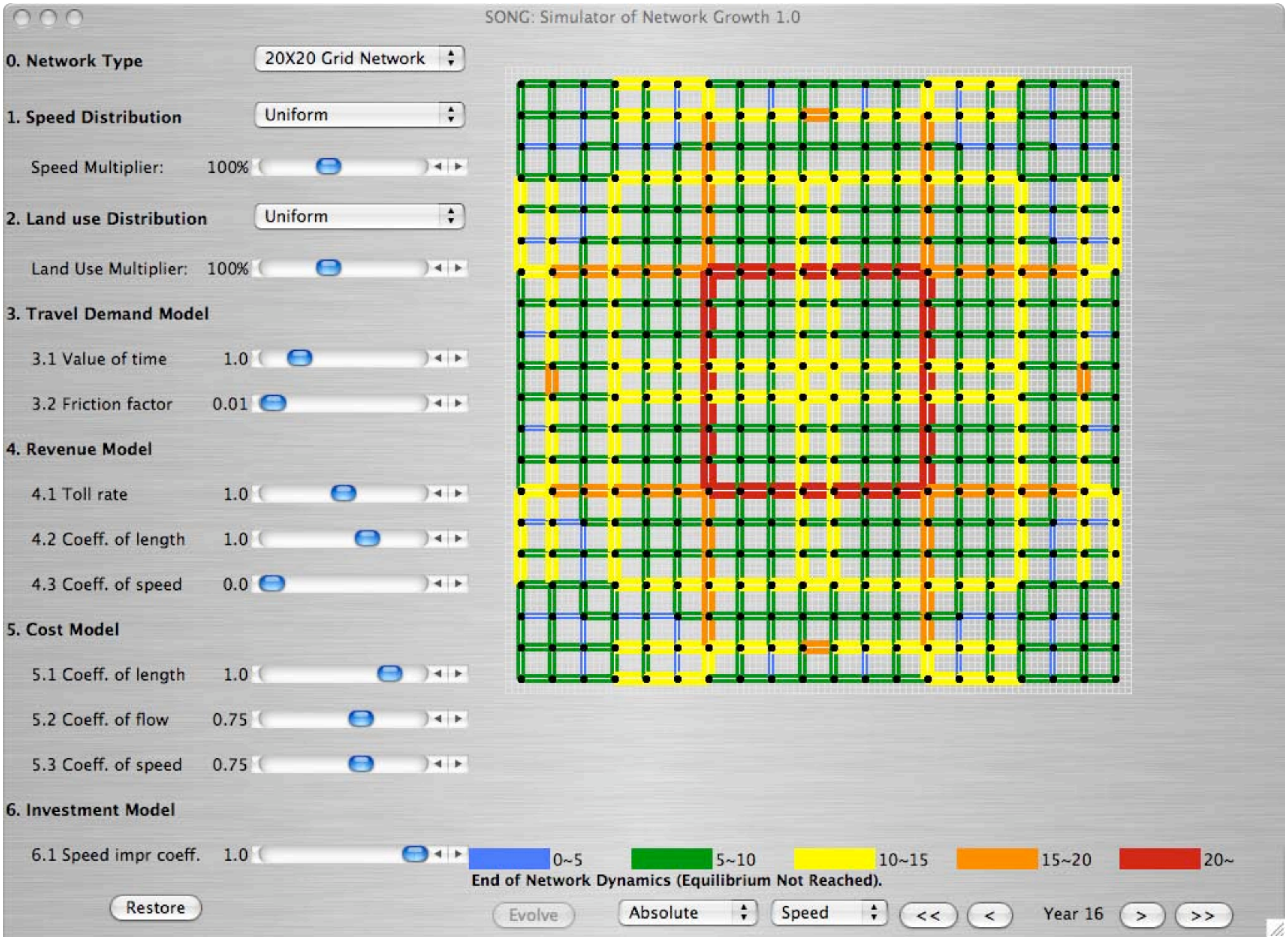
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Restore
0~5
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10~15
15~20
20~
End of Network Dynamics (Equilibrium Not Reached).
Evolve
Absolute
Speed
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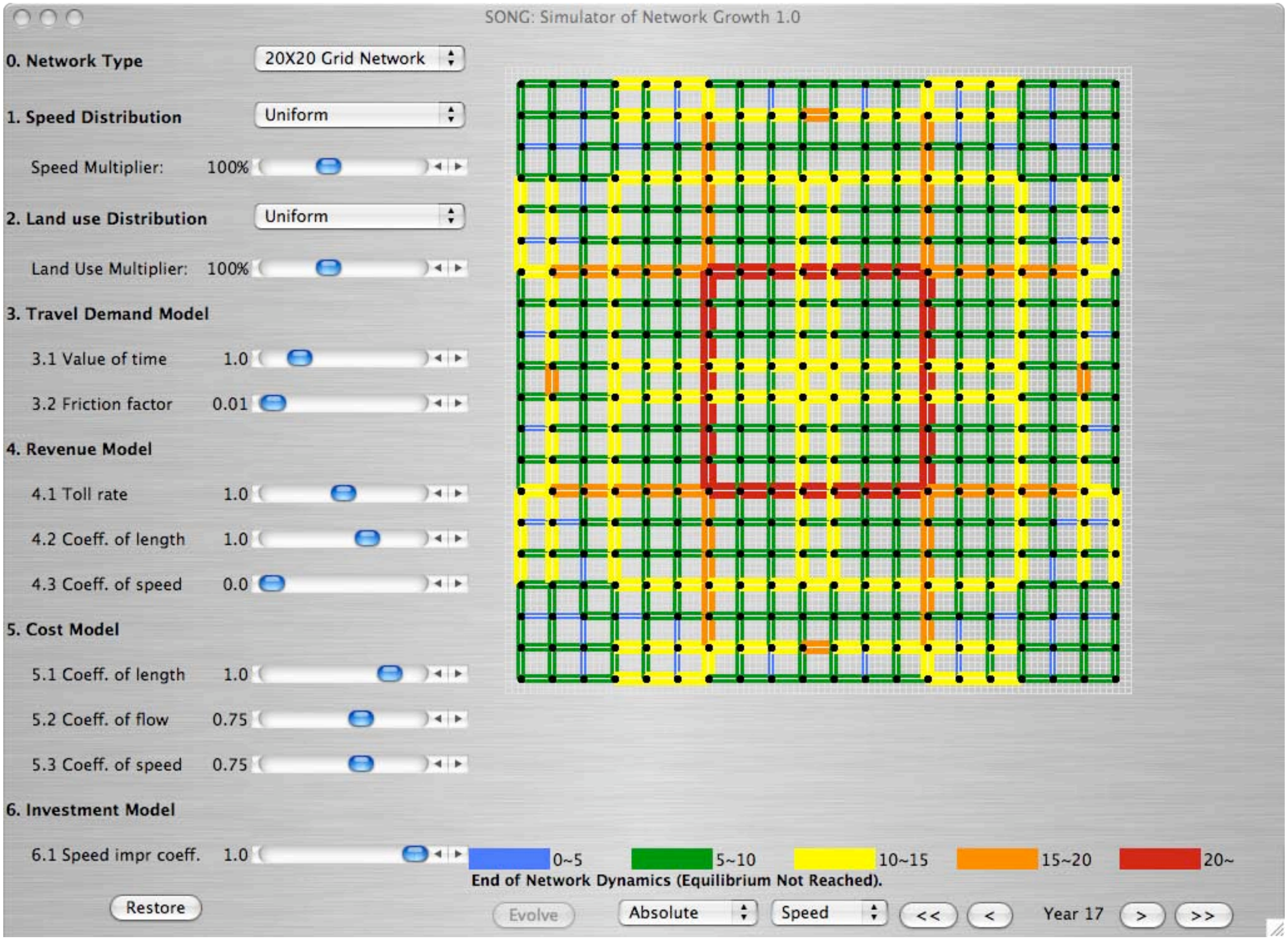
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Restore
0~5
5~10
10~15
15~20
20~
End of Network Dynamics (Equilibrium Not Reached).
Evolve
Absolute
Speed
<<
<
Year 17
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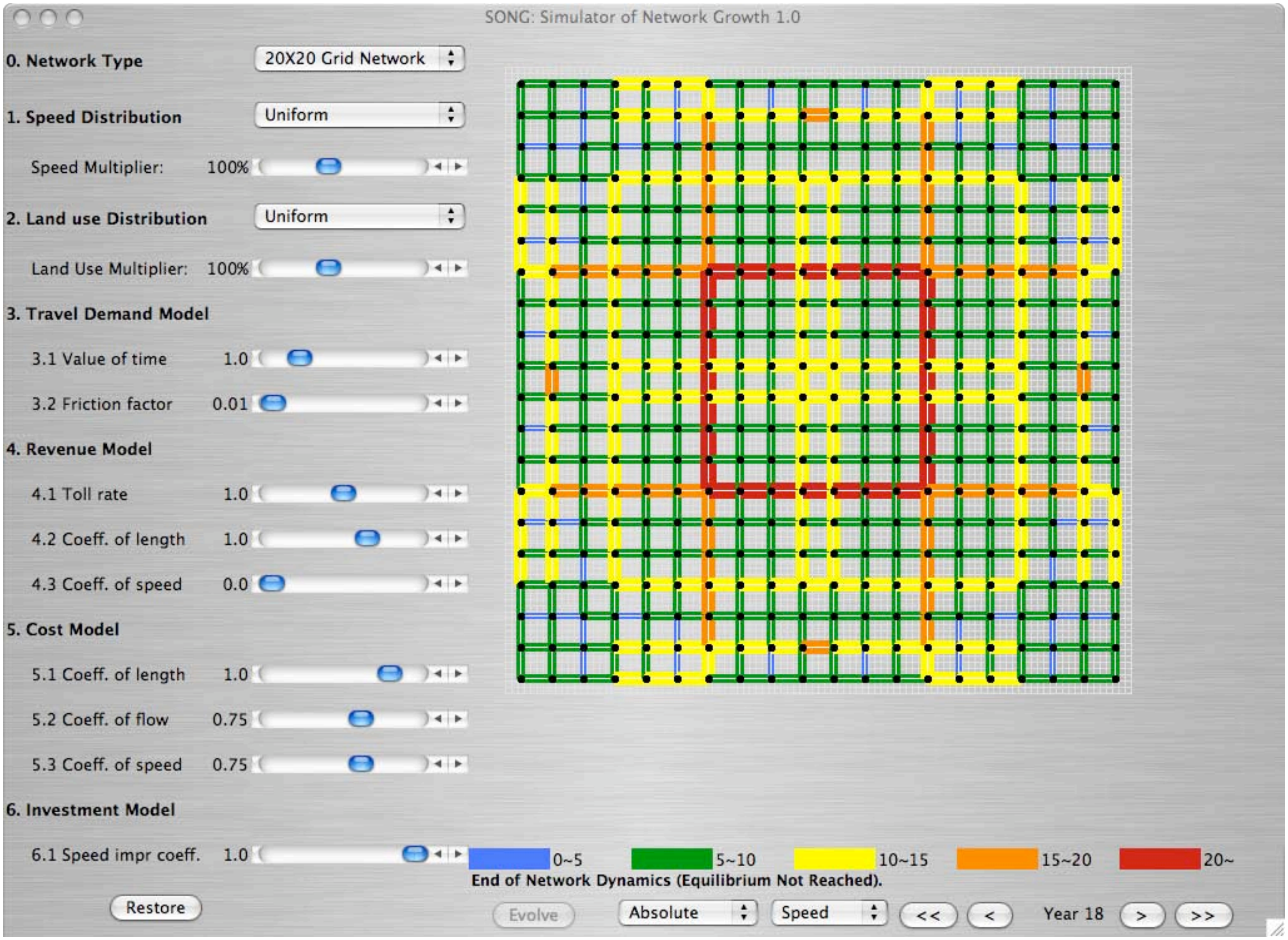
SONG: Simulator of Network Growth 1.0
0. Network Type
20X20 Grid Network
1. Speed Distribution
Uniform
Speed Multiplier: 100%
2. Land use Distribution
Uniform
Land Use Multiplier: 100%
3. Travel Demand Model
3.1 Value of time 1.0
3.2 Friction factor 0.01
4. Revenue Model
4.1 Toll rate 1.0
4.2 Coeff. of length 1.0
4.3 Coeff. of speed 0.0
5. Cost Model
5.1 Coeff. of length 1.0
5.2 Coeff. of flow 0.75
5.3 Coeff. of speed 0.75
6. Investment Model
6.1 Speed impr coeff. 1.0
Restore
0~5
5~10
10~15
15~20
20~
End of Network Dynamics (Equilibrium Not Reached).
Evolve
Absolute
Speed
<<
<
Year 18
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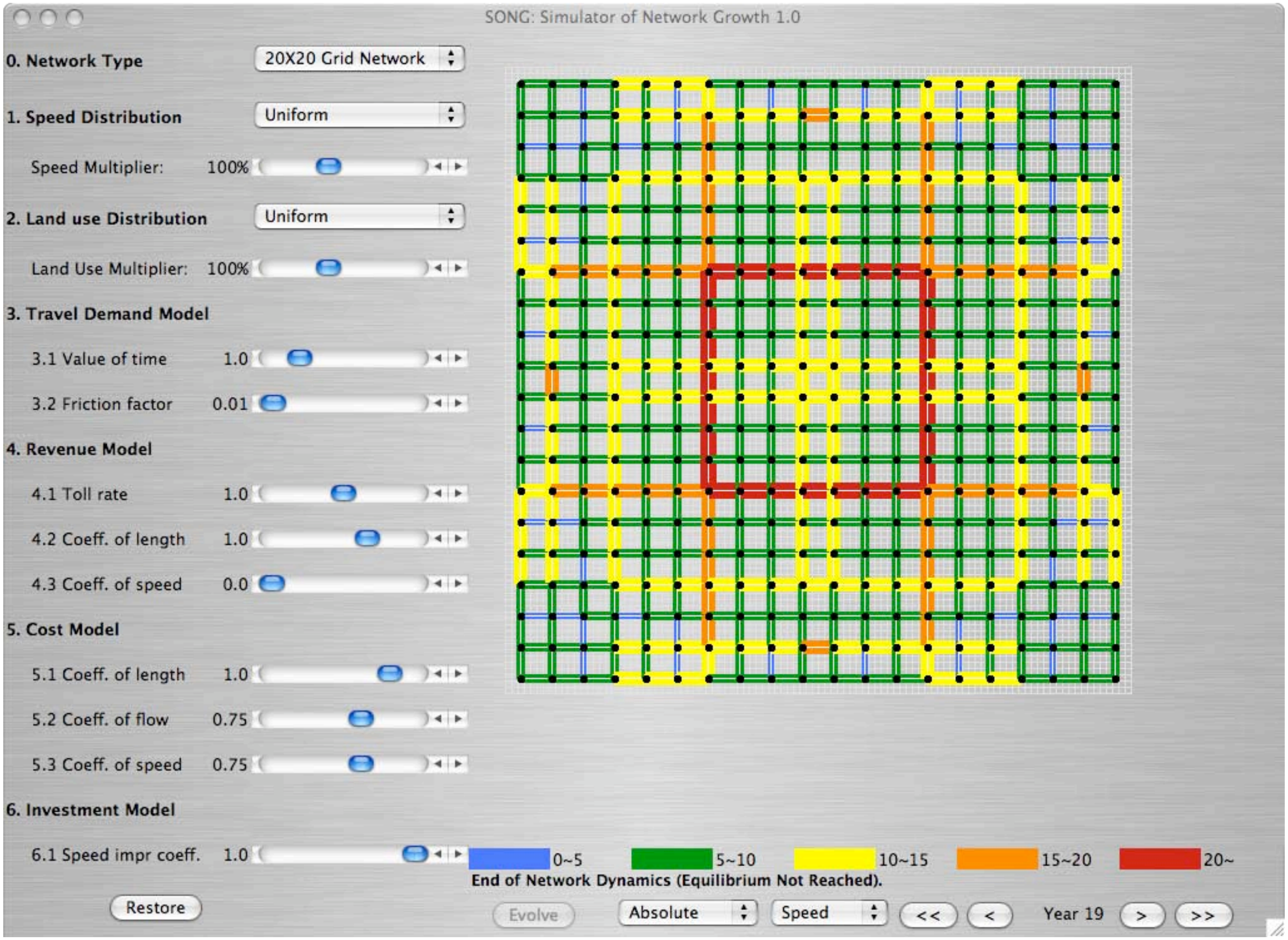
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End of Network Dynamics (Equilibrium Not Reached).
Evolve
Absolute
Speed
<<
<
Year 19
>
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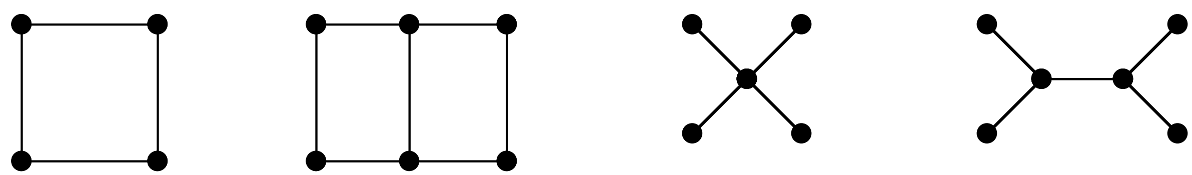
Hierarchy

- Succeeded in growing transportation networks from undifferentiated links to differentiated structure
- Sufficiency of simple link based revenue and investment rules in mimicking a hierarchical network structure
- Hierarchical structure of transportation networks is a property of boundaries & asymmetries not entirely a design
- Investment policy can drive shape of hierarchy
- Model scales to metropolitan area

Connectivity

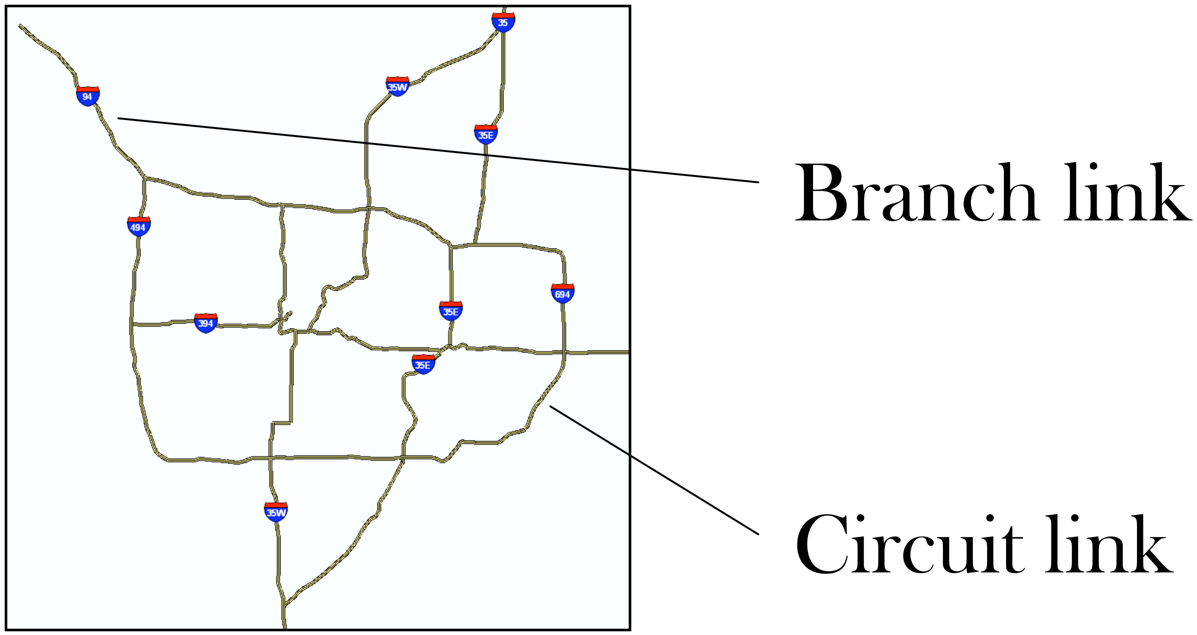
- Existing connectivity measures
  - Basic topological measures: the number of edges (e), the number of vertices (v), the number of maximally connected components, number of circuits
  - Alpha, Beta, Gamma indexes
- Need measures to identify and quantify connection patterns of networks

- Measures of effectiveness (MOEs)
  - Cumulative change of social welfare
  - Network mobility measures (TTT, VKT)
  - Accessibility



Ring | Web | Star | Hub-and-spoke

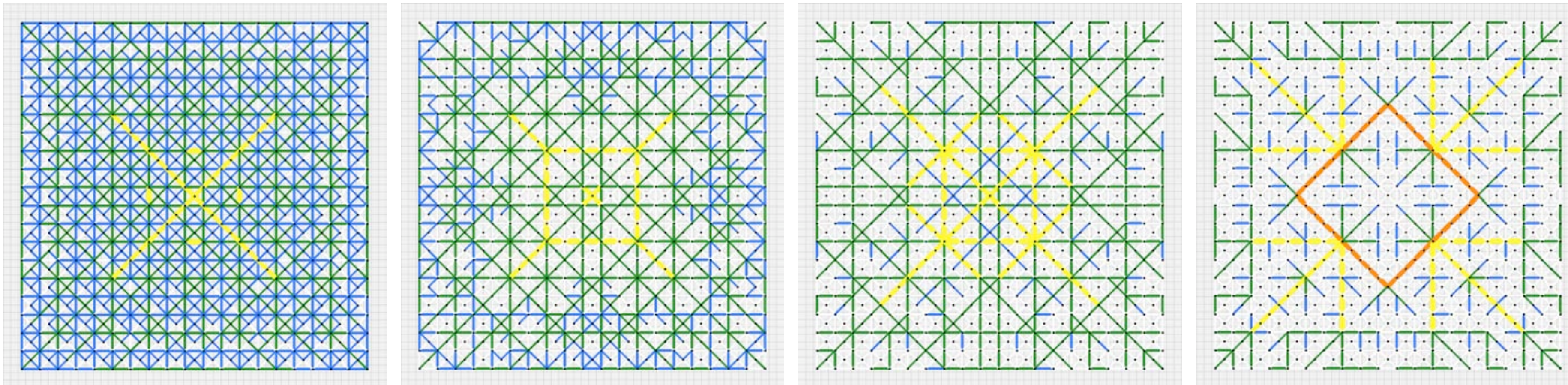
Measures of connection patterns



- Branch link vs. Circuit link
- Branch, web, ring
- Circuitness ($\phi_{circuit}$) and treeness (ϕ_{tree})
- Beltness (ϕ_{belt})

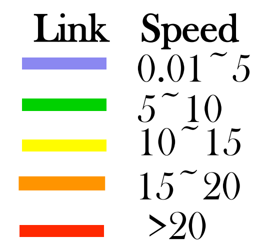
Weakest Link Model

- Begin with ultra-connected network
- Each iteration, kill the weakest link
- Allow rest of links to grow or shrink as the investment rules dictate
- Repeat
- (stop when obtain minimally connected network, I.e. tree)



Iteration 50 | Iteration 150 | Iteration 200 | Iteration 250

		Iteration #	50	150	200	250
The Whole Network	H	Speed entropy	3.041	2.801	2.927	3.263
	γ	The gamma index	0.863	0.569	0.451	0.334
	D	Density	3.677	2.269	1.518	1.003
The Arterial Network	e	Number of edges	80	80	200	240
	n	Number of vertices	45	41	97	120
	u	Number of circuits	0	1	4	1
	z	Number of subgraphs	5	2	1	1
	ϕ_{prim}	The mileage ratio of the primary subgraph	86.4%	91.7%	100.0%	100.0%
	N_{ring}	Number of rings	0	1	0	1
	N_{web}	Number of webs	0	0	1	0
	ϕ_{tree}	The mileage ratio of branching roads	100.0%	41.4%	55.4%	70.7%
	ϕ_{ring}	The mileage ratio of rings	0.0%	58.6%	0.0%	29.3%
	ϕ_{web}	The mileage ratio of webs	0.0%	0.0%	44.6%	0.0%



Experiment C2

Efficiency: asymmetric case

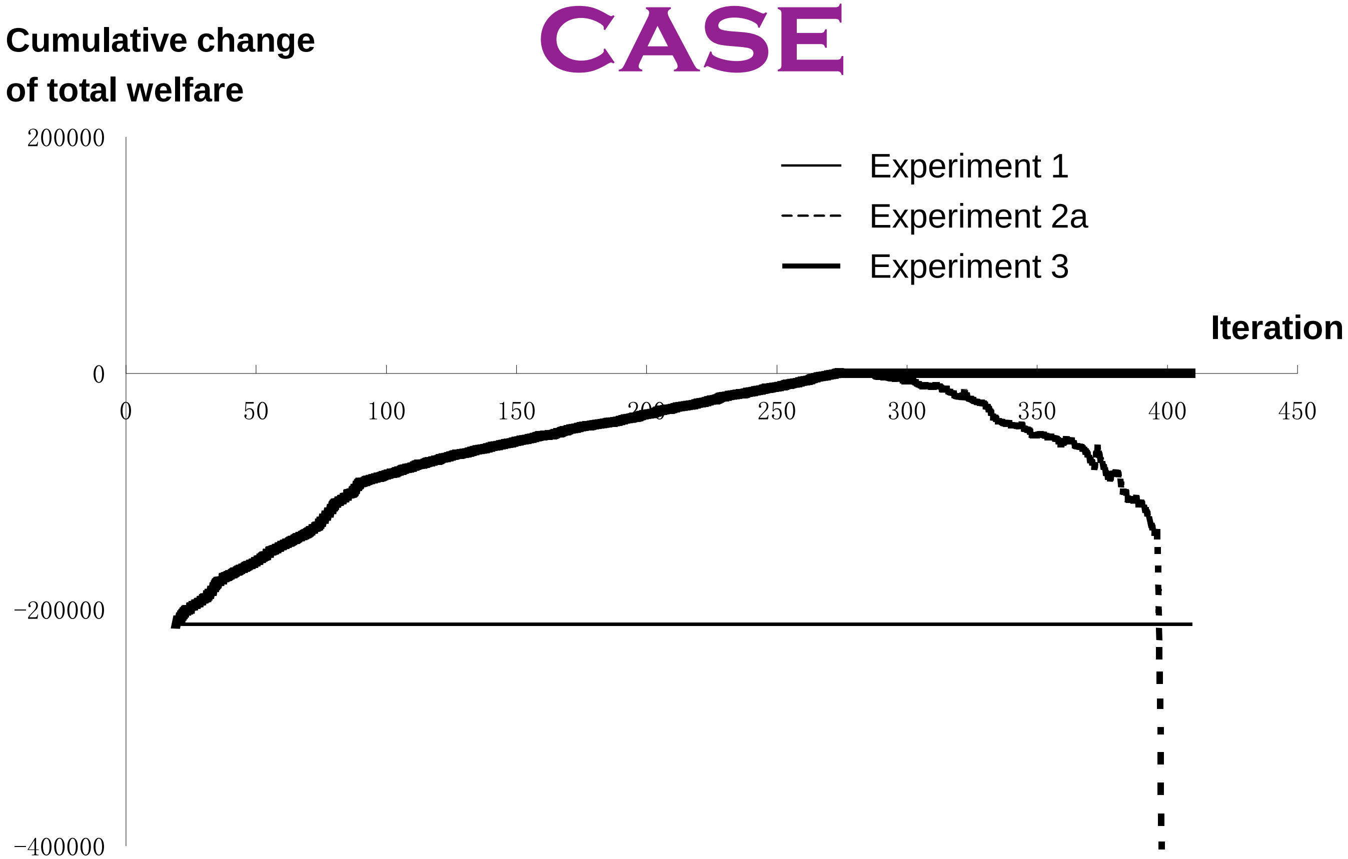
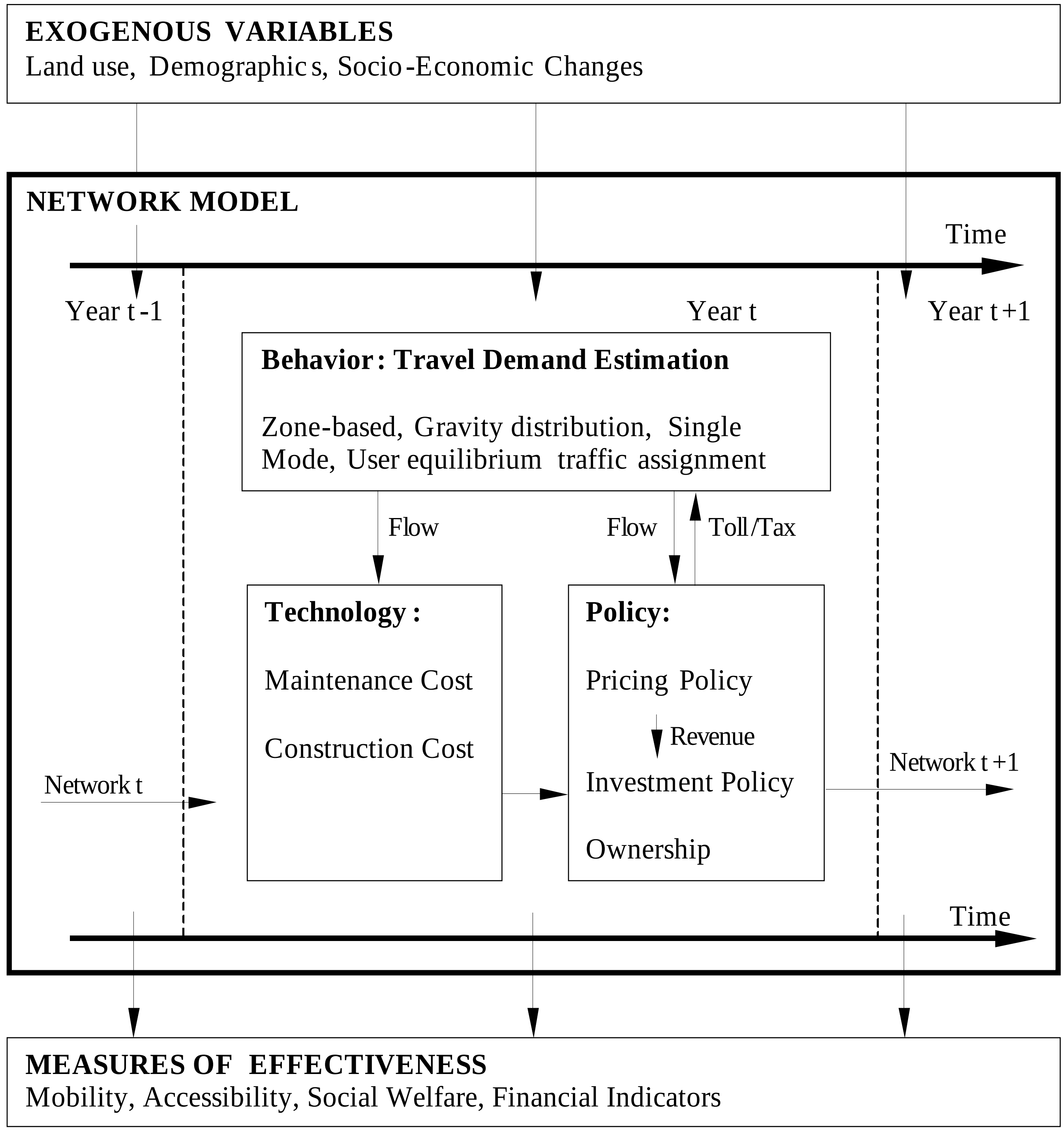


Figure 4. The cumulative change of total welfare over time for the asymmetric case

Topology

- Topologies of road networks can be measured, compared, and traced over time.
- The measures of entropy and connection patterns complement existing topological measures of hierarchy and connectivity.
- Improved measurement of network topologies can disclose collective features of road network spatially and temporally and thus guide long-term transportation plans and designs.

Testing Pricing And Ownership



Centralized Ownership

Pricing Policy

- Fuel taxes, Registration fees, Distance-based tolls

  = Average cost pricing

Investment Strategy

- Construction budget = Revenue – Maintenance Cost
- Priority: Links with the highest benefit/cost ratios

  Solve $\underset{\Delta Capacity}{Maximize} \quad BCRatio(\Delta Capacity)$

  for each link

- At the end of each fiscal year: Budget = Expenditure

Decentralized Ownership: Pricing

A Dynamic Pricing Game among All Roads

- Uncertainty and incomplete information

Profit-Maximizing Pricing through Adaptive Learning

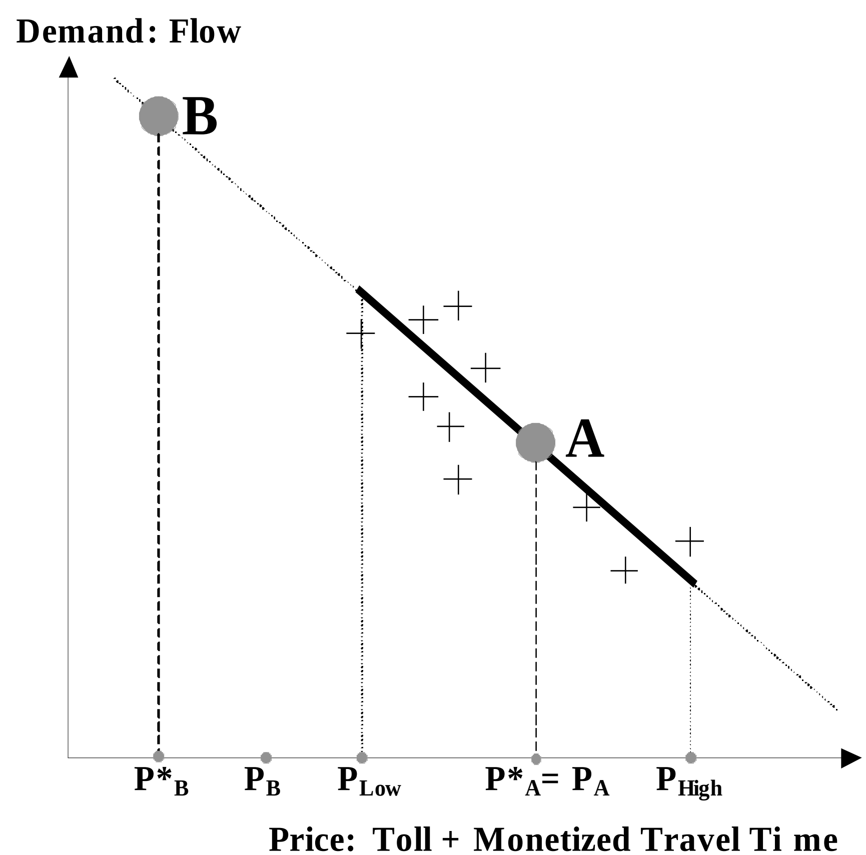
1. Estimate a demand curve based on (price, flow) data in previous years for each link;
2. Solve Maximize Profit(price);
3. Case A: $P_{Low} < Price^* < P_{High}$

   New Price = Price*

   Case B: $Price^* < P_{Low}$ or $> P_{High}$

   New Price = $P_{Low}(1 - j)$

   or = $P_{High}(1 + j)$



Decentralized Ownership: Investment

Rate of Return

- (Lifecycle Revenue – Lifecycle Cost)/Capital Cost
- Links can borrow or earn interest through a "Bank" agent
- If Rate of return > interest rate → Borrow & Build capacity

  Otherwise → Pay off loan or Save

Profit Estimation for Capacity Expansion

- Consider two sources of additional profit after expansion

  1. Ability to charge higher tolls
  2. Ability to attract more users

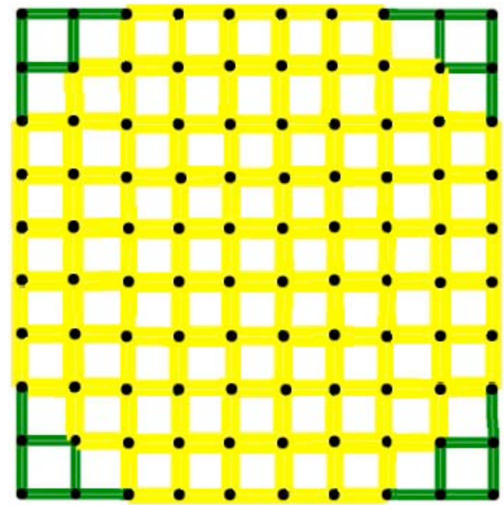
Fixed Demand: Equilibrium Capacity

Equilibrium Capacity on a 10x10 Grid Network

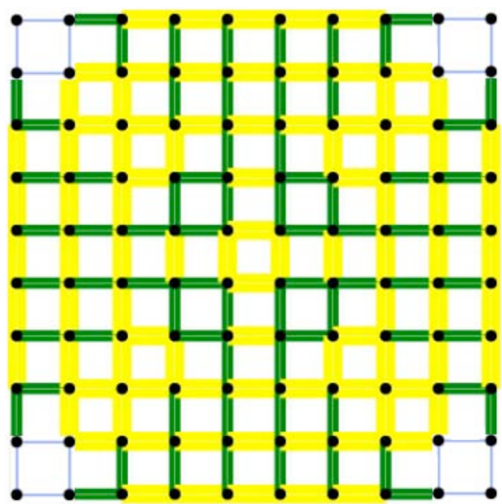
Capacity (veh/hr)

- 0 ~ 1000
- 1000 ~2000
- 2000 ~ 4000
- 4000 ~ 8000
- > 8000

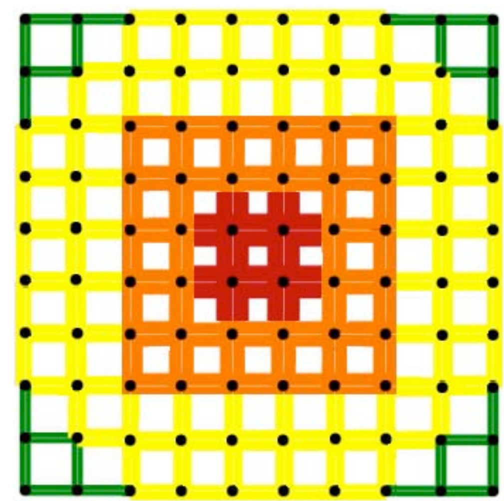
Socially Optimal



Centralized Ownership



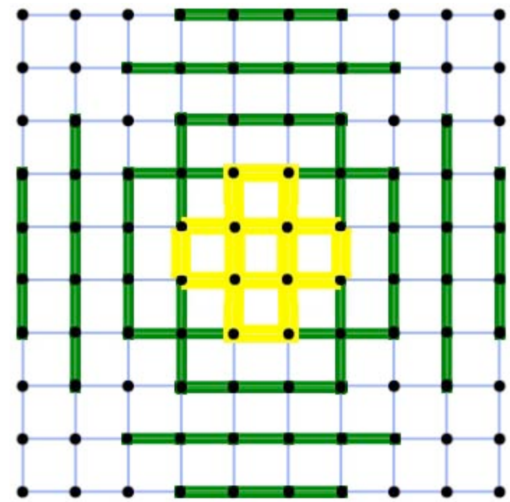
Decentralized Ownership



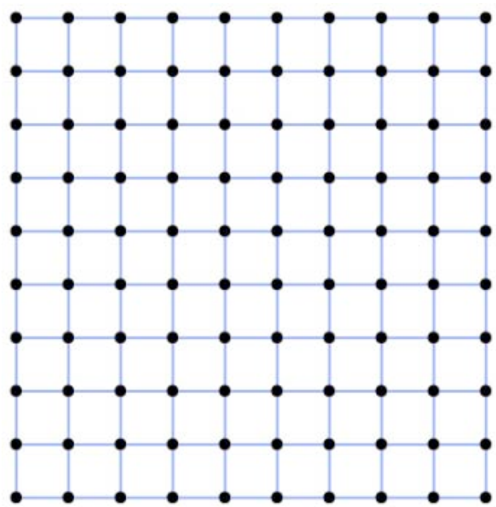
Fixed Demand: Equilibrium Tolls

Equilibrium Toll

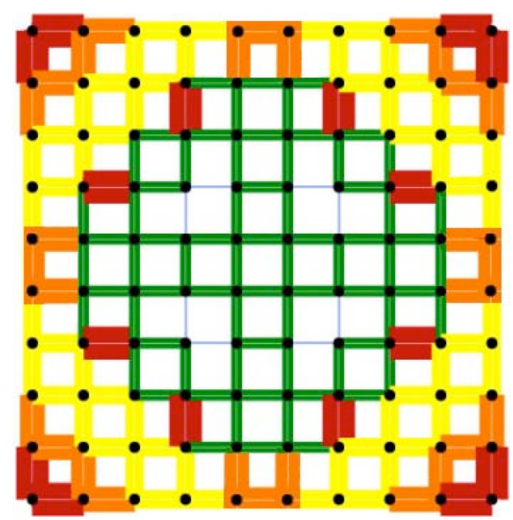
Socially Optimal



Centralized Ownership

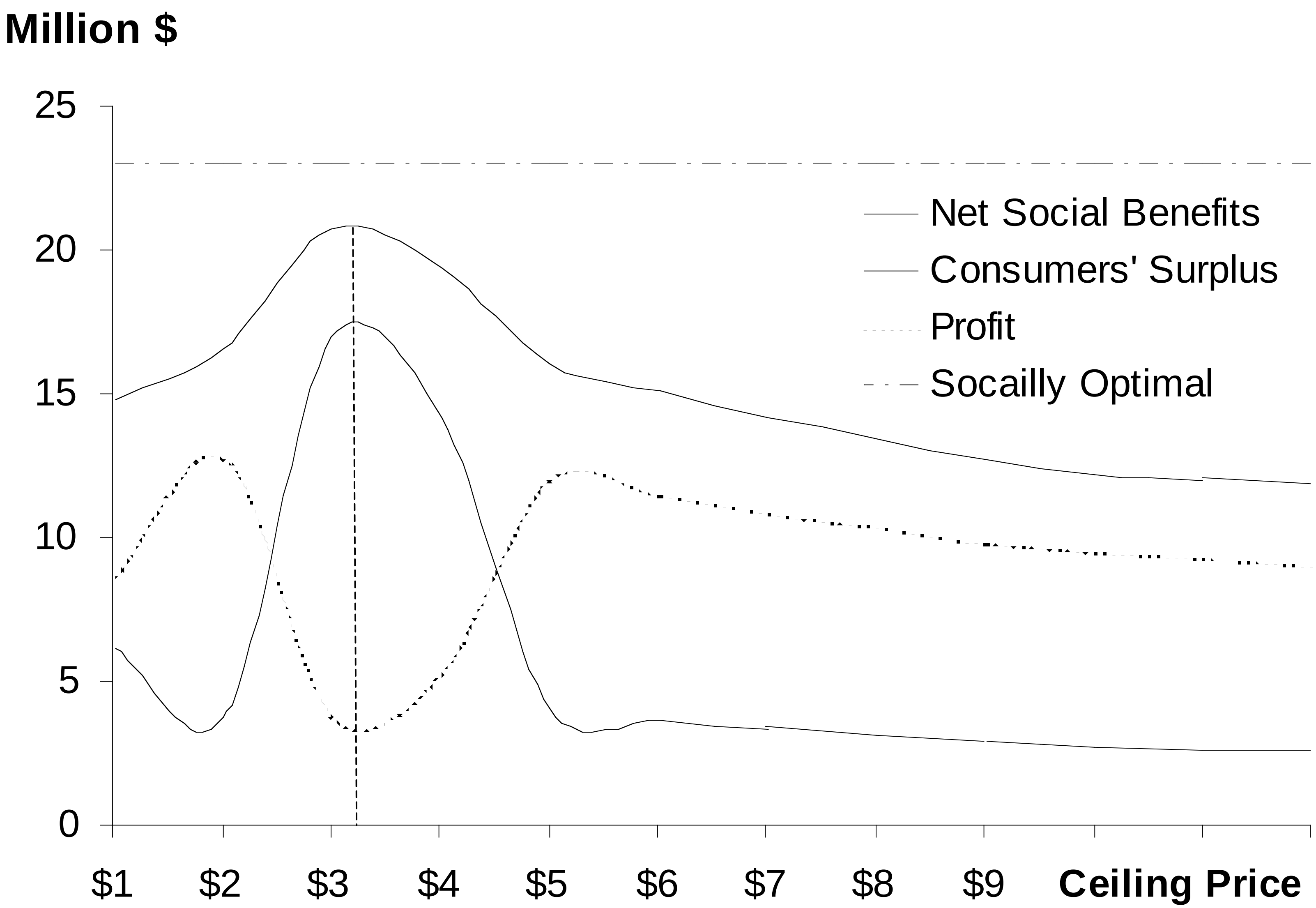


Decentralized Ownership

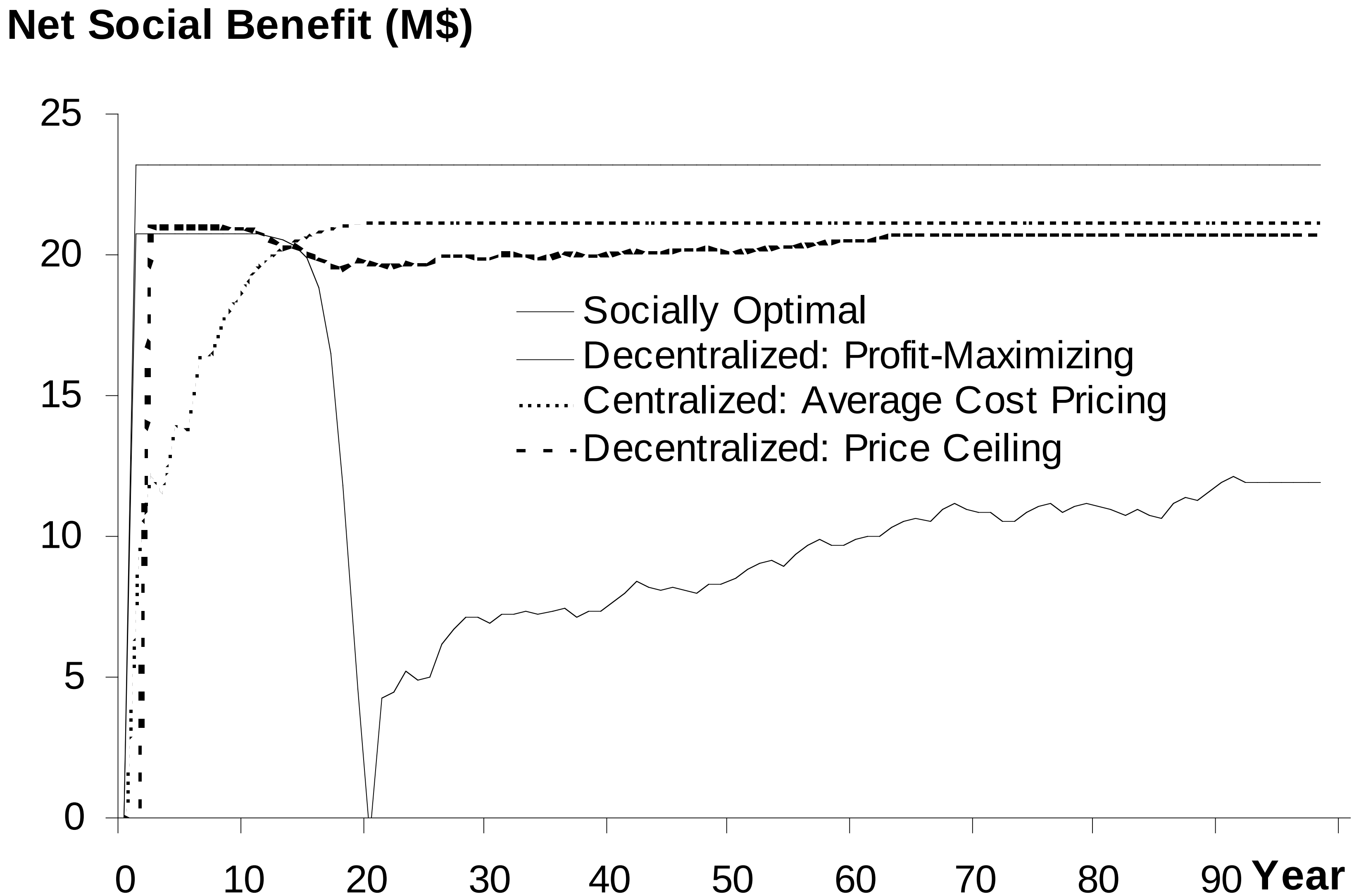


Decentralized Ownership with Regulation

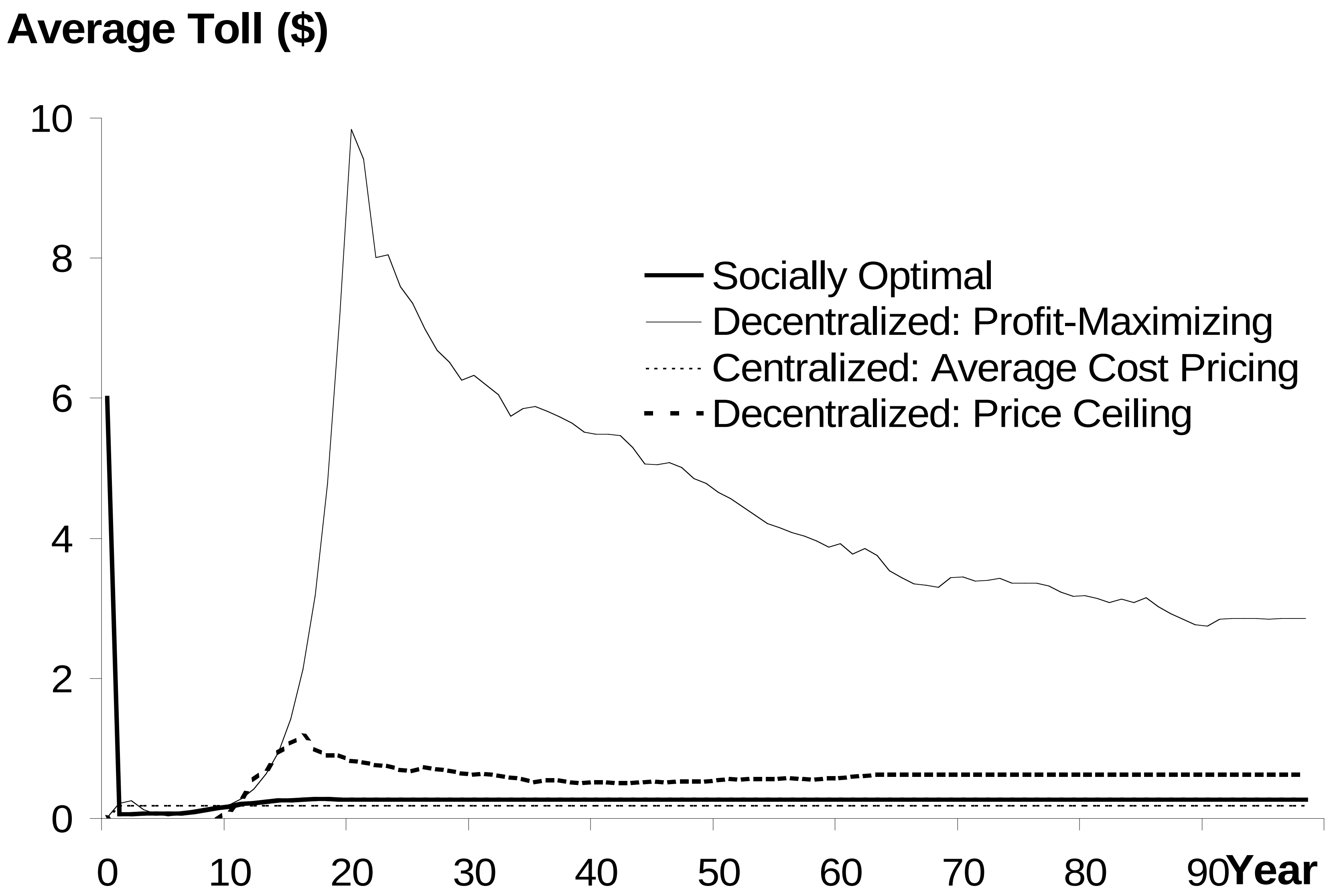
Determination of the Optimal Ceiling Price



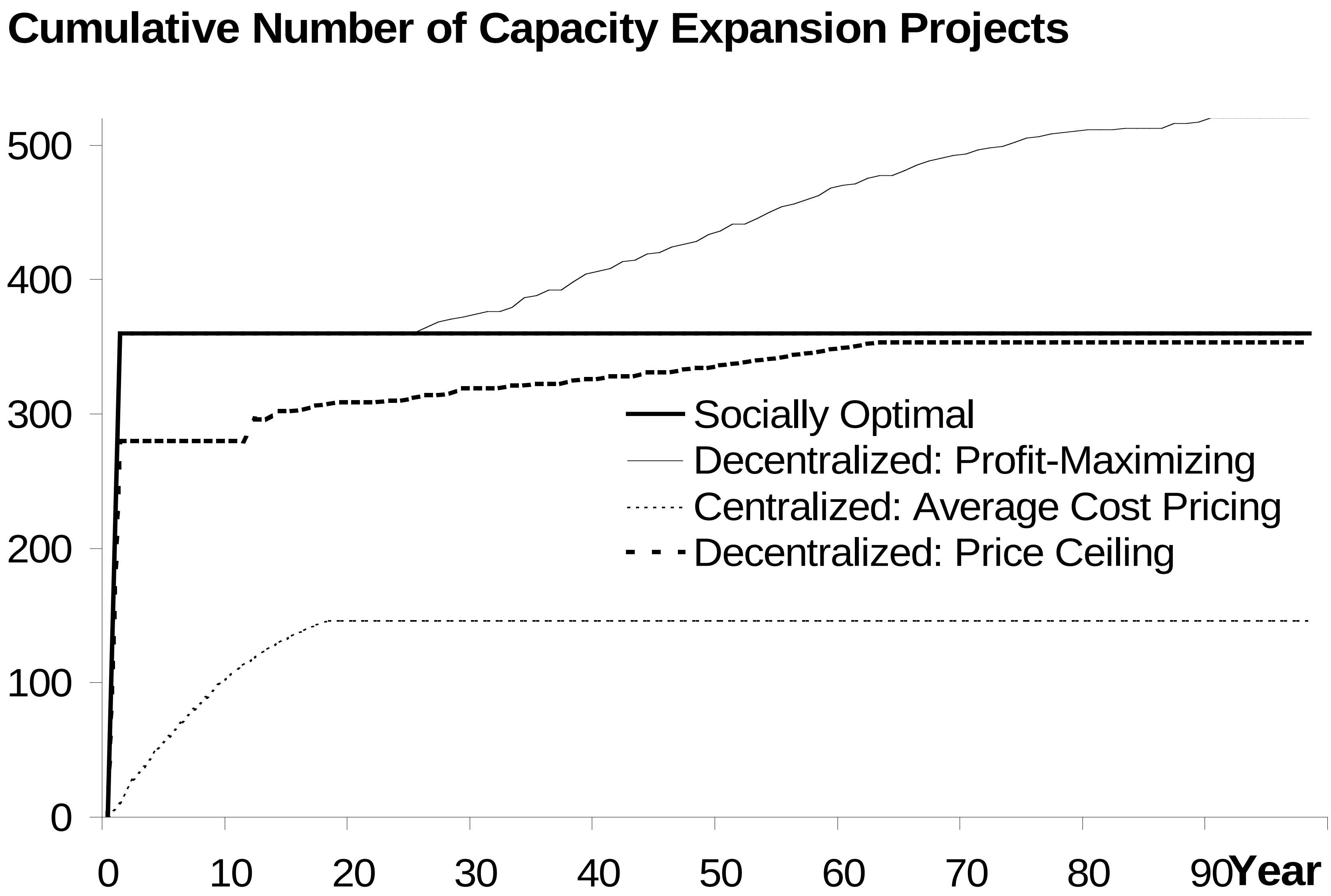
Evolution of Benefit



Evolution Of Tolls



Evolution of Capacity



Ownership

Nothing is perfect

	Pros	*Cons*
Centralized	Status quo	Low tolls, Ineffective
	Cost recovery	Sub-optimal capacity
Decentralized	Responsiveness	High tolls
	Market-oriented	Risk of over-investment

When appropriate regulation is imposed (e.g. Pmax)

and/or travel demand is steadily increasing (e.g. 3%)

Results are in favor of decentralized market-oriented approach

Conclusions

- This framework allows understanding of changing spatial structure of networks.
- Model of transportation network (with flows moving across space and time as function of costs) along with changing capacity and price of connections (nodes and links) is a model of the economy in miniature.
- Future research could extend this platform to more realistically understand the dynamic relationships between firms (links) and markets (nodes).

- Yerra, Bhanu and Levinson, D. (2005) The Emergence of Hierarchy in Transportation Networks. *Annals of Regional Science* 39 (3) 541-553
- Zhang , Lei and David Levinson (2005) Road Pricing on Autonomous Links *Journal of the Transportation Research Board* (in press).
- Levinson, David and Bhanu Yerra (2005) Self Organization of Surface Transportation Networks *Transportation Science* (in press)
- Chen, Wenling and David Levinson (2006) Effectiveness of Learning Transportation Network Growth Through Simulation. *ASCE Journal of Professional Issues in Engineering Education and Practice* Vol. 132, No. 1, January 1, 2006
- Zhang , Lei and David Levinson. (2004a) An Agent-Based Approach to Travel Demand Modeling: An Exploratory Analysis *Transportation Research Record: Journal of the Transportation Research Board* #1898 pp. 28-38
- Levinson, D. and Karamalaputi, Ramachandra (2003) Predicting the Construction of New Highway Links. *Journal of Transportation and Statistics* Vol. 6(2/3) 81-89
- Levinson, D and Karamalaputi, R (2003), Induced Supply: A Model of Highway Network Expansion at the Microscopic Level *Journal of Transport Economics and Policy*, Volume 37, Part 3, September 2003, pp. 297-318
- Parthasarathi, P, Levinson, D., and Karamalaputi, Ramachandra (2003) Induced Demand: A Microscopic Perspective *Urban Studies* Volume 40, Number 7 June 2003 pp. 1335-1353
- Zhang, Lei David M. Levinson (2005) Pricing, Investment, and Network Equilibrium (05-0943) presented at 84th Annual Meeting of Transportation Research Board in Washington, DC, January 9-13th 2005.
- Zhang, Lei , David M. Levinson (2005) Investing for Robustness and Reliability in Transportation Networks (05-0897) presented at 84th Annual Meeting of Transportation Research Board in Washington, DC, January 9-13th 2005 and presented at 2nd International Conference on Transportation Network Reliability. Christchurch, New Zealand August 20-22, 2004.
- Levinson, D, and Wei Chen (2004) Area Based Models of New Highway Route Growth *ASCE Journal of Urban Planning and Development* (in press)
- Levinson, D. (2003) The Evolution of Transport Networks. Chapter 11 (pp 175-188) /\in *Handbook 6: Transport Strategy, Policy and Institutions* (David Hensher, ed.) Elsevier, Oxford
- Xie, Feng and David Levinson (2005) The Weakest Link: A model of the decline of surface transportation networks *Transportation Research part E* (in press)

RESEARCH PAPERS

•Xie, Feng and David Levinson (2005) Measuring the Topology of Road Networks *Geographical Analysis* (in press)

•Xie, Feng and David Levinson (2005) The Topological Evolution of Road Networks

•Montes de Oca, Norah and David Levinson (2005) Network Expansion Decision-making in the Twin Cities *Transportation Research Record* (in press)

•Levinson, David and Bhanu Yerra (2005) How Land Use Shapes the Evolution of Road Networks

•Levinson, David and Wei Chen (2005) Paving New Ground: A Markov Chain Model of the Change in Transportation Networks and Land Use Chapter 11.*Access to Destinations (Elsevier)*

•Zhang, Lei and David Levinson (2005) The Economics of Transportation Network Growth

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