Automated Optimal Balancing of Traffic Volume Data for Large Access-Controlled Highway Networks and Freeway-to-Freeway Interchanges

John W. Shaw, PE (Corresponding Author)
Researcher
Traffic Operations & Safety Laboratory
University of Wisconsin
1415 Engineering Drive
Madison, WI 53706
Phone: (414) 227-2150
jwshaw@wisc.edu

David A. Noyce
Professor
Department of Civil & Environmental Engineering
University of Wisconsin
1204 Engineering Hall
1415 Engineering Drive
Madison, WI53706
Phone: (608) 265-1882
noyce@engr.wisc.edu

Word Count (4342 + 2 Figures×250 + 3 Tables×250) = 5592 words

ABSTRACT

Traffic analysts and modelers frequently need to combine street and highway volume data from multiple days and sources in order to assemble a complete data set for a study area. Pro-rata methods have traditionally been used to "balance" inconsistent data sets for limited-access facilities, but the pro-rata procedure has several limitations and cannot readily be applied to complicated roadway geometries such as freeway-to-freeway interchanges. Mathematical optimization of the data set using algorithms such as the GRG2 solver can address many of these situations and allows rapid balancing of large roadway networks for multiple time periods. Optimization also allows a second (perhaps less reliable) set of mainline observations to be considered in the balancing process. We selected minimization of the sum of the GEH for each observation as the objective function and implemented the procedure in a spreadsheet (it could also be implemented as a database-driven application). Optimization produced more favorable GEH values than pro-rata methods, indicating better fit to the original data set. Optimization results combining GRG2 and GEH appear to be reasonably stable and tolerant of fluctuations in the input data values attributable to typical traffic counting devices. Additional research is necessary to quantify the effects of severe outliers on the optimization results and determine which combination of objective function and search algorithm is "best" for various types of networks.

INTRODUCTION

Traffic analysts and modelers frequently need to combine street and highway volume data from multiple days and sources in order to assemble a complete data set for a study area. The underlying data often varies considerably in terms of age and quality. As a result, field-collected traffic volumes for a freeway system (or other access-controlled corridor) frequently contain mathematical inconsistencies which can hamper the analytical process and slow the convergence of data-intensive operations such as Origin-Destination Matrix Estimation (ODME). Manually balancing a large freeway network is extremely labor-intensive and has no unique mathematical solution.

Figure 1 shows some observed daily volumes along one direction of a freeway section in southeastern Wisconsin. If we start with the volume at the Automatic Traffic Recorder (ATR) station on the left side of the figure and proceed in the direction of travel, adding the on-ramp volumes and subtracting the off-ramp volumes, the running total (shown in purple on the bottom line) does not match the observed volume at the downstream ATR on the right side of the figure (in blue on the upper line).

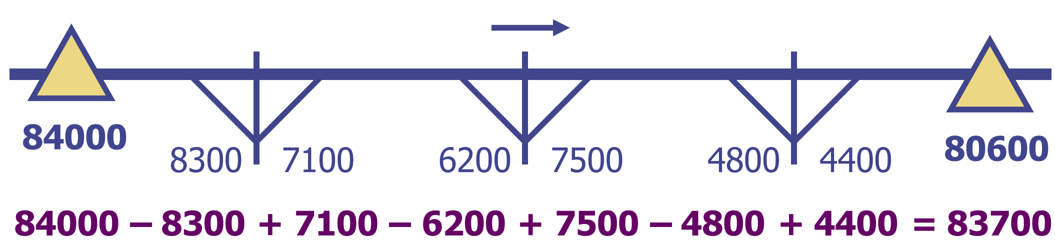

Figure 1: Example of an imbalance between upstream ATR volume (represented by triangle) and running total of entrance and exit volumes at next downstream ATR.

The inconsistencies highlighted in Figure 1 arise primarily from the fact that the network was not counted simultaneously. Instead, the figure represents typical Wisconsin data collection practice: a combination of annual averages from mainline ATRs (continuous counts) and 48-hour ramp counts collected on various days using portable pneumatic tube counters. A location such as this might also have short-duration mainline counts, volumes from Freeway Traffic Management System (FTMS) sensors, toll-tag reader data, weigh-in-motion stations, intersection turning movement counts, etc. Since data is collected at different times with various technologies (and differing quality-acceptance criteria), it must be adjusted or "balanced" to obtain a mathematically consistent data set.

This paper discusses a procedure for balancing traffic volume data for an access-controlled facility such as a freeway. If directional data is available, balancing could also be applied to arterials or other non-access-controlled facilities, provided that traffic generators such as side streets and major driveways are treated in a manner similar to "ramps" in the discussion that follows.

GOALS OF THE BALANCING PROCESS

Our primary applications for the balanced data are HCM capacity analysis, work zone traffic planning, and OD matrix estimation for microsimulation modeling (where prior experience indicated that balancing the input data resulted in faster convergence and reduced the risk of oscillation between conflicting numerical targets). Therefore our goals include the following:

- Compute balanced volumes for all access-controlled roadway geometries, including freeway-to-freeway interchanges (system interchanges) and frontage road systems, as well as ordinary freeway segments.
- Facilitate simultaneous balancing of all access-controlled facilities in a large network (i.e. multi-county regions or statewide).
- Support balancing over multiple time periods, e.g. 12 months × 24 hours × 4 day types (weekday, Friday, Saturday, Sunday).
- Utilize a spreadsheet or a database application, without requiring external tools such as a travel demand forecasting model.
- Reconcile data from all available sources including ATRs, FTMS sensors, and short-duration counts.
- Impute missing data for short segments such as between ramps at a diamond interchange.
- Temper the effects of outliers (such as counts collected on non-representative days) and errors such as equipment problems.
- Utilize prior-year data as a surrogate in case of detector failure or similar circumstances.
- Provide an indicator of possible sensor problems.

PREVIOUS AUTOMATED BALANCING METHODS

Several authors have addressed the question of balancing turning movement count data along an arterial corridor. Hauer, *et al* (*1*) developed a technique for solving and balancing turning movement volumes based on an initial estimate of turning proportions supplied by the user. The method was further elaborated by Lin & Rasp (*2*) and developed into a spreadsheet application called TURNS5 for the Florida Department of Transportation (*3*). Ren & Rahman (*4*) applied a fuzzy logic approach to the problem of forecasting future turning movement counts, given a mainline forecast and an existing turning pattern. Xin (*5*) developed a desktop application called ArtBalT for balancing existing intersection turning movement counts along a short arterial corridor (up to 6 typical intersections) by "proportioning the extra link volume (i.e. the volume difference between the total inflow and total outflow of a link) among any movements that can be changed." Liao (*6*) expanded Xin's logic to allow pro-rata balancing along a "linear arterial network with virtually no intersection size limit." A caveat to these methods is the potential existence of unmonitored access points between intersections, potentially violating the assumed equality between upstream output volumes and downstream input volumes.

In the context of access-controlled facilities, the 2001 FHWA Traffic Monitoring Guide (TMG) (*7*) suggests the use of a pro-rata adjustment process for freeway mainline balancing. In the TMG procedure, pairs of ATRs are selected and used as "anchor points"; counts at the anchors are assumed to be accurate and pro-rata ramp volume adjustments are made in order to balance volumes along the segment.

$$I = A_1 + \sum_{i=1}^{n} R_i - A_2 \qquad (1)$$

$$\hat{R}_j = R_j - I \times R_j \div \sum_{i=1}^{n} |R_i| \qquad (2)$$

Where:

A_1 , A_2 = Mainline volumes at anchor points

R_i = Observed volume on ramp *i* (>0 for entrance ramps and <0 for exit ramps)

R_j = Observed volume on ramp *j* (>0 for entrance ramps and <0 for exit ramps)

$\hat{R}_i$ = Adjusted volume on ramp *i* (>0 for entrance ramps and <0 for exit ramps)

$\hat{R}_j$ = Adjusted volume on ramp *j* (>0 for entrance ramps and <0 for exit ramps)

In Table 1, Column C shows the way the TMG's pro-rata method distributes the imbalance of +3100 vehicles from the Figure 1 data (in this case the 3.1% mainline imbalance results in an 8.1% adjustment to each entrance and exit ramp). Xin (*5*) utilized this method in a desktop data-preparation application called TradaX. The method was also utilized on a regional scale in an unpublished spreadsheet-based tool called BALT developed by Nam & Ornek for the Southeast Wisconsin Freeway System Operational Assessment.

In the mid 1990s Zhao *et al* (*8*) developed a traffic data reconciliation system for the Connecticut DOT. Their algorithm focuses primarily on the use of balancing techniques to impute traffic volumes for unmonitored mainline links when there are a small number of ATRs serving as anchor points and a full set of counts for freeway ramps. In addition, they provided logic using least squares regression to resolve discrepancies at mainline count stations where redundant data is available. A significant limitation of their method is that the objective function requires an *a priori* estimate of the variance (or standard deviation) of each site's volumes, and assumes that the errors are normally distributed, which is not always the case.

A related approach was taken by Kwon *et al* (*9*), who used matrix-based weighted least squares regression to solve the balancing problem and impute missing data values for access-controlled linear corridors. The method is primarily intended for use with Freeway Traffic Monitoring Systems (FTMS) that have relatively close detector spacing and continuous data feeds. A limitation of the method is that it requires establishing confidence levels (excellent/good/fair/poor) for each traffic detector station in advance. Setting confidence levels may be difficult in the case of "planning" type data that combines observations from different days, since the analyst may be unaware of sensor problems or ephemeral undercounts or overcounts caused by incidents or events. The method also requires a corridor-wide standardized flow value and, like the Zhao method, assumes that errors are normally distributed.

TABLE 1. Examples of balancing calculation methods and resulting GEH scores.

A	B		C			D			E		
Segment Description	**Raw Observed Data**		**Pro-Rata Adjustment**			**Two Constrained Anchors** Branch & Bound Solver			**No Anchor Constraints** GRG2 Solver		
	Volume	**Running Total**	**Volume**	**Running Total**	G_D	**Volume**	**Running Total**	G_D	**Volume**	**Running Total**	G_D
ATR on Segment A	84000	84000	84000		0.0	84000	84000	0.0	81376	81376	2.9
Exit Ramp 1	-8300		-8972		2.3	-8764		1.6	-8300		0.0
Between Ramps at Exit 1		75700		84672			75236			73076	
Entrance Ramp 1	7100		6525		2.2	6501		2.3	6896		0.8
Basic Segment B		82800		85246			81737			79971	
Exit Ramp 2	-6200		-6702		2.0	-6659		1.8	-6187		0.1
Between Ramps at Exit 2		76600		85748			75078			73784	
Entrance Ramp 2	7500		6893		2.3	6896		2.3	7284		0.8
Basic Segment C	82000	84100		86355	4.7		81974	0.0		81069	1.0
Exit Ramp 3	-4800		-5189		1.7	-5261		2.1	-4799		0.0
Between Ramps at Exit 3		79300		86744			76713			76270	
Entrance Ramp 3	4400		4044		1.7	3887		2.5	4251		0.7
ATR on Seg D (Calculated)		83700	80600		0.0		80600	0.0		80521	0.1
ATR on Seg D (Observed)	80600										
Imbalance		*+3100*		*0*			*0*			*0*	
Total					**16.9**			**12.6**			**6.3**

Currently the pro-rata technique discussed in the TMG appears to be the most widely applied balancing methodology. While pro-rata adjustments are expedient and relatively simple to implement, the method has some important limitations:

1. In practice it is unlikely that counting imbalances are actually proportional for all sites along a corridor. Often a large part of an imbalance is attributable to a few sites where data was affected by a problem such as poor sensor placement, equipment malfunction, incidents, or construction. Stressing the need for checking the result of balancing, the TMG cautions, "an equipment error in any of the initial counts may have caused the problem with the ending difference, and the error is then further aggravated by the adjustment."

2. The pro-rata process places 100% confidence in the anchor point data. In practice, even when ATRs are used as anchors the data is not completely accurate, especially as sensors degrade with age.
3. The TMG recommends that there be no more than 5 interchanges between anchors, but this is not always feasible due to limited ATR infrastructure (especially in rural areas).
4. The pro-rata process is difficult to implement for complicated roadway geometries, such as freeway-to-freeway interchanges (where each ramp affects three or more computations). Frontage roads that re-join the mainline also present computational challenges.
5. The pro-rata process requires an ATR station or other trusted observation at each end of section that is being analyzed. Such data may not exist, for example, at stub-ends of the network or jurisdictional boundaries.
6. The pro-rata process cannot take advantage of non-anchor observations on basic roadway segments. Consequently it cannot use additional data that helps clarify which of the many possible solutions is the most appropriate.

Some of the considerations enumerated above also apply to the Zhao and Kwon techniques.

THE GEH FORMULA

Development of an automated balancing process requires a robust measure of the difference between adjusted and unadjusted traffic counts. While percent difference is a frequently-used metric, it can be problematic because of the wide range of volume values typically encountered in highway systems. For example, adjusting a ramp volume from 40 veh/hr to 50 veh/hr generates the same percent difference as adjusting a mainline volume from 4000 veh/hr to 5000 veh/hr, but the effect on the system as a whole is quite different. Thus, a potential pitfall with using percent difference as the objective function for optimization is that a ramp with a severe undercount might not be adjusted sufficiently.

To address this issue, in the 1970s Geoff E. Havers of the Greater London Council (*10*) proposed a heuristic measure of volume difference now known as the GEH formula. The British Highways Agency Design Manual for Roads & Bridges describes it as "a form of Chi-squared statistic that incorporates both relative and absolute errors [and] can be calculated for individual links or groups of links." (*11*). In the United Kingdom it is accepted as "a standard measure of the 'goodness of fit' between [two sets of traffic] flows. Unlike comparing flows using percentage difference, the GEH statistic places more emphasis on larger flows than on smaller flows."(*12*) Low GEH values indicate similarity between the original and adjusted values, while high GEH indicates greater change. Table 2 shows rule-of-thumb interpretations of the GEH value that were developed for comparing observed and modeled values in travel demand foresting models; we apply similar interpretations to the differences between the original and adjusted values from the balancing process. (Detectors that generate high GEH values in the balancing process may require evaluation or repair).

TABLE 2. Interpretations of GEH values from the Saturn travel demand forecasting software user's manual (8).

Value	Comment	Example 1	Example 2
GEH = 1.0	"Excellent"	±65 in 4,000	±25 in 500
GEH = 2.0	"Good"	±130 in 4,000	±45 in 500
GEH = 5.0	"Acceptable"	±325 in 4,000	±120 in 500
GEH =10.0	"Rubbish!"	±650 in 4,000	±250 in 500

The GEH formula for hourly traffic flows is:

$$G_H = \sqrt{\frac{2(v - \hat{v})^2}{v + \hat{v}}} \tag{3}$$

Where:
G_H = GEH for hourly volume
v = Unadjusted hourly volume
$\hat{v}$ = Adjusted hourly volume

The GEH formula was originally intended for use with hourly traffic flows. To preserve the typical GEH acceptance thresholds (“5 is OK”, “10 is not”) when balancing daily traffic volumes (e.g. AADT), researchers can use the approximation that peak hourly volume is on the order of 10% of the daily volume. In this case the GEH formula becomes:

$$G_D = \sqrt{\frac{0.2V^2 - 0.4V\hat{V} + 0.2\hat{V}^2}{V + \hat{V}}} \tag{4}$$

Where:
G_D = GEH for daily volume
V = Unadjusted daily volume
$\hat{V}$ = Adjusted daily volume

OPTIMIZATION FOR BALANCING

To meet the previously-stated goals and overcome the limitations of pro-rata adjustment, we developed an automated balancing method that is based on mathematical optimization. In this optimization problem, our goal is to minimize the difference between the original and adjusted traffic volumes, subject to the constraint that the volumes in the network must balance (traffic inputs equal traffic outputs).

To compute the objective function we used the sum of the GEH for all locations where an observed count was available; this allows us to consider data from a second (perhaps less reliable) set of mainline observations (such as short-duration mainline counts or FTMS sensor output), without treating those volumes as anchors. We applied the G_H formula to hourly data (such as the AM peak hour) and the G_D formula to daily data (equation 5 illustrates the use of G_H).

Optionally, we may constrain certain volumes to match known values at highly-trusted anchor sites, but in contrast to the TMG procedure we do not need to use every ATR as an anchor. The primary advantage of setting anchors is to allow the balancing process to be completed piecewise, for example balancing freeway-to-freeway interchanges before moving on to general freeway segments.

With GEH minimization as the objective, this process can be expressed mathematically as:

$$\min\left(\sum\sqrt{\frac{2(A_i - \hat{A}_i)^2}{(A_i + \hat{A}_i)}} + \sum\sqrt{\frac{2(R_j - \hat{R}_j)^2}{(R_j + \hat{R}_j)}}\right) \text{ subject to: } \hat{A}_1 + \sum\hat{R}_j = \hat{A}_t \tag{5}$$

and optionally subject to: $\hat{A} = A$ for trusted sites

Where:
A = Unadjusted mainline volume (typically from ATRs)
$\hat{A}$ = Adjusted mainline volume

R = Unadjusted ramp volume
$\hat{R}$ = Adjusted ramp volume
t = Station ID at terminus of the analysis section

IMPLEMETING THE BALANCING PROCESS

Procedural Steps

The main steps in this process are as follows:

1. Importing the raw data from various traffic databases.
2. Computing the imbalance in the imported data set by means of running totals.
3. Adjusting the counts using mathematical optimization, subject to the constraint that the imbalance must be zero.

We implemented volume balancing in a spreadsheet for the freeway systems in some relatively large metropolitan areas (i.e. metro Milwaukee and metro Green Bay). A mainframe application that can directly access the raw traffic data also warrants consideration, especially if balancing of multiple time periods or very large areas is desired. In either case, an optimization algorithm needs to be available. For spreadsheet-based balancing we used the Solver add-in for Microsoft Excel, which uses the Generalized Reduced Gradient (GRG2) algorithm for optimizing nonlinear problems and the Branch & Bound (B&B) method for optimizing integer problems (*13*). In our data sets the GRG2 algorithm tended to produce results more quickly than the B&B method, but GRG2 had a greater chance of stopping on a local minimum (instead of the global minimum).

Output Examples

The results of optimizing the Figure 1 data set are shown in Columns D and E of Table 1. For illustrative purposes, it is assumed that a 48-hour mainline count was available in Segment C, with an observed average daily volume of 82,000 (since it is included in the GEH calculations this supplemental observation influences the optimization). Column D shows the results with the B&B algorithm and the constraint that both ATRs are treated as unchangeable anchors that must exactly match the original observations (as in the pro-rata method). Compared to the pro-rata method, total G_D for this freeway section drops from 16.9 to 12.6 (average G_D drops from 1.9 to 1.4). Column E shows the result of relaxing the anchor constraint and using the GRG2 algorithm; in this case total G_D drops to 4.4 (average G_D drops to 0.5). In both cases the original unadjusted volumes were used as the trial solution and GEH minimization was used as the objective function.

Table 3 shows the results of a GRG2 based optimization for a three-leg freeway-to-freeway interchange located near Bellevue, Wisconsin. ATR sites identified by green shading were treated as unchangeable anchors. Grey text identifies values that appear in the calculations a second (or third) time because they involve two (or more) legs of the interchange. This problem cannot be solved using the pro-rata method, but an optimization-based solution is feasible. The table reflects some realities of this 2006 data set: the “raw” I-43 North-to-South and South-to-North through movements are estimates because no relevant field data was available, but the optimization refines these estimates as part of the process of establishing a mathematically consistent volume set.

Additional Considerations

If a corridor consists only of service interchanges and ordinary freeway segments, each travel direction can be balanced separately. If the study area includes freeway-to-freeway interchanges, the entire area must be balanced simultaneously. (Special care must be taken when coding freeway-to-freeway movements to assure that the adjusted volumes are consistent for all routes involving that movement.)

The procedure is tolerant of a limited amount of missing or surrogate count data. For example, most Wisconsin freeways have counts on ramps and basic freeway segments, but not on the short segments between ramps at an interchange, and this situation is easily accommodated as in the Table 1 example. The process is also reasonably tolerant of the use of old data as a surrogate when some of the newer data is unavailable (for example, combining current mainline counts with a combination of old and new ramp counts). Nevertheless, there are some instances where balancing is thwarted by incomplete data. For example, if an exit splits into two downstream ramps and only one of them has been counted, the missing ramp's volume must be collected in order to determine the total volume (without this data the balancing process can produce misleading results or fail entirely).

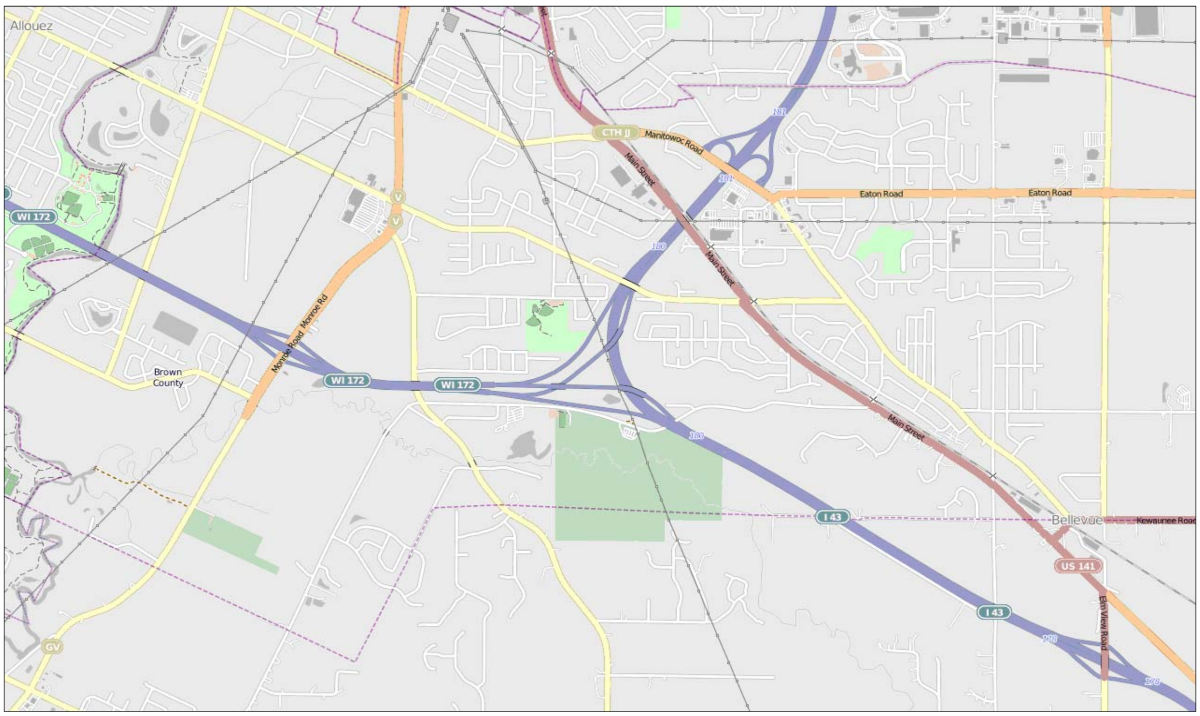

Figure 2. Map of I-43 & WIS 172 Interchange, Bellevue, Wisconsin

TABLE 3. Balancing example for three-leg freeway-to-freeway interchange (see Figure 2 for map).

BELLEVUE INTERCHANGE						
Southbound Thru	**Raw**	**Balanced**		**Change**	**% Chng**	**G_D**
I-43 SB Btwn Manitowoc Rd & Bellevue System Interchange [Anchor]	*21945*	*21945*		0	0.0%	0.0
System Exit Ramp I-43 SB to STH 172 WB	18000	18245		245	1.4%	0.6
I-43 North-South Thru Movement	3700	3700		0	0.0%	0.0
System Ramp STH 172 EB to I-43 SB	9526	9247		-279	-2.9%	0.9
I-43 SB Btwn Bellevue IC and Elm View Rd (CTH MM) [Anchor]	*12948*	*12948*		0	0.0%	0.0
Calculated Volume	*13471*	*12948*				1.5
Imbalance	*524*	*0*				
Southbound Turning Westbound	**Raw**	**Balanced**		**Change**	**% Chng**	**G_D**
I-43 SB Btwn Manitowoc Rd & Bellevue System Interchange [Anchor]	21945	21945		0	0.0%	0.0
I-43 North-South Thru Movement	3700	3700		0	0.0%	0.0
System Exit Ramp I-43 SB to STH 172 WB	18000	18245		245	1.4%	0.6
System Ramp from I-43 NB to STH 172 WB (Bellevue IC)	10077	9462		-615	-6.1%	2.0
STH 172 WB Btwn Bellevue IC and Monroe Rd	22500	27707		5207	23.1%	10.4
Monroe Rd (CTH GV) Exit Ramp	5300	5300		0	0.0%	0.0
Between Ramps at Monroe Rd Interchange		22407				
Monroe Rd (CTH GV) Entrance Ramp	4550	4550		0	0.0%	0.0
STH 172 WB Bridge over East River [Anchor]	*26957*	*26957*		*0*	*0.0%*	*0.0*
Calculated Volume	*27572*	*26957*				12.9
Imbalance	*615*	*0*				
Eastbound Turning Northbound	**Raw**	**Balanced**		**Change**	**% Chng**	**G_D**
STH 172 EB Bridge over East River [Anchor]	*26957*	*26957*		*0*	*0.0%*	*0.0*
Monroe Rd (CTH GV) Exit Ramp	4550	4995		445	9.8%	2.0
Between Ramps at Monroe Rd Interchange		21962				
Monroe Rd (CTH GV) Entrance Ramp	5500	4988		-512	-9.3%	2.2
STH 172 EB Btwn Monroe Rd and Bellevue Interchange	22500	26950		4450	19.8%	8.9
System Ramp STH 172 EB to I-43 SB	9526	9247		-279	-2.9%	0.9
System Ramp from STH 172 EB to I-43 NB (Bellevue IC)	18600	17702		-898	-4.8%	2.1
I-43 South-North Thru Movement	*3700*	*3486*		*-214*	*-5.8%*	*1.1*
I-43 NB Btwn Bellevue Interchange & Manitowoc Rd *[Anchor]*	21188	21188		0	0.0%	0.0
Calculated Volume	*22081*	*21188*				17.4
Imbalance	*893*	*0*				
Northbound Thru	**Raw**	**Balanced**		**Change**	**% Chng**	**G_D**
I-43 NB Btwn Elm View Rd (CTH MM) and Bellevue IC [Anchor]	*12948*	*12948*		0	0.0%	0.0
System Ramp from I-43 NB to STH 172 WB (Bellevue IC)	10077	9462		-615	-6.1%	2.0
I-43 South-North Thru Movement	3700	3486		-214	-5.8%	1.1
System Ramp from STH 172 EB to I-43 NB (Bellevue IC)	18600	17702		-898	-4.8%	2.1
I-43 NB Btwn Bellevue Interchange & Manitowoc Rd [Anchor]	*21188*	*21188*		0	0.0%	0.0
Calculated Volume	*21471*	*21188*				5.2
Imbalance	*283*	*0*				
Northbound Turning Westbound	**Raw**	**Balanced**		**Change**	**% Chng**	**G_D**
I-43 NB Btwn Elm View Rd (CTH MM) and Bellevue IC [Anchor]	12948	12948		0	0	0
I-43 South-North Thru Movement	3700	3486		-214	-5.8%	1.1
System Ramp from I-43 NB to STH 172 WB (Bellevue IC)	10077	9462		-615	-6.1%	2.0
System Exit Ramp I-43 SB to STH 172 WB	18000	18245		245	1.4%	0.6
STH 172 WB Btwn Bellevue IC and Monroe Rd	22500	27707		5207	23.1%	10.4
Monroe Rd (CTH GV) Exit Ramp	5300	5300		0	0.0%	0.0
Between Ramps at Monroe Rd Interchange		22407				
Monroe Rd (CTH GV) Entrance Ramp	4550	4550		0	0.0%	0.0
STH 172 WB Bridge over East River [Anchor]	*26957*	*26957*		0	0	0
Calculated Volume	*26498*	*26957*				14.1
Imbalance	*-460*	*0*				
Eastbound Turning Southbound	**Raw**	**Balanced**		**Change**	**% Chng**	**G_D**
STH 172 EB Bridge over East River [Anchor]	26957	26957		0	0.0%	0.0
Monroe Rd (CTH GV) Exit Ramp	4550	4995		445	9.8%	2.0
Between Ramps at Monroe Rd Interchange		21962				
Monroe Rd (CTH GV) Entrance Ramp	5500	4988		-512	-9.3%	2.2
STH 172 EB Btwn Monroe Rd and Bellevue Interchange	22500	26950		4450	19.8%	8.9
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System Ramp STH 172 EB to I-43 SB	9526	9247		-279	-2.9%	0.9
I-43 North-South Thru Movement	3700	3700		0	0.0%	0.0
I-43 SB Btwn Bellevue IC and Elm View Rd (CTH MM) [Anchor]	*12948*	*12948*		0	0.0%	0.0
Calculated Volume	*13007*	*12948*				16.2
Imbalance	*60*	*0*				
Grand Total						**80.2**

VALIDATION

While validation of this methodology is difficult because the "true" traffic volumes for an unbalanced data set are inherently unknown, we conducted some sensitivity testing to explore the stability of the optimization.

Expected Levels of Input Data Variation

In 2011 McGowen & Sanderson (*14*) compared volume results from pneumatic tube traffic counters with manual counts and output from portable magenetometers; they reported that for daily traffic volumes, "the total error of the road tube counts was less than 4 percent." Older British research summarized in DMRB (*15*) provides a similar assessment, "the current best 'working' estimate of the accuracy of measurement in the number of vehicles that passed an automatic traffic counter is that the 95% confidence interval of a count of longer than 12 hours duration is on the order of ±5% of the total count. This assumes that the counter was installed and maintained to the standards laid down in the 'Manual of Automatic Traffic Counting Practice.'"

Sensitivity Test Results

Using the GRG2 solver and treating the balanced Bellevue data from Table 3 as the "ground truth", we increased and decreased the input observed value for one of the freeway-to-freeway ramps (STH 172 EB to I-43 SB) by -5% and +5%; in both cases the optimization restored the volumes to their previous values. We also applied simulated random fluctuations in the range of -5% to +5% to nine input volumes in the Bellevue data set. Amongst 10 simulation runs, the G_D between the original values and the re-optimized "with fluctuation" values ranged from 0.0 to 2.2 (average 0.6); the RMSE between the original and re-optimized values was 3%. Therefore, the optimization process appears to be reasonably consistent and stable, at least if the input data set is free of severe outliers.

CONCLUSIONS

Automated traffic volume count balancing using mathematical optimization can be applied successfully to resolve data discrepancies in access-controlled corridors and networks. GEH values are generally lower than the results of the "standard" pro-rata procedure recommended in the 2001 Traffic Monitoring Guide, indicating better fit to the original data set. In general there is no unique solution to the optimization problem, so the results will differ depending on the optimization algorithms and objective function that are selected. We found that combining a GEH based objective with a GRG2 search produced stable results. A shortcoming of GRG2 is that it is sensitive to the trial solution and sometimes selects a local optimum rather than the global optimum. Additional research is necessary to determine whether a GEH-based objective function and a GRG2 search is the "best" combination for all networks. Further work is necessary to quantify the effects of severe outliers on the optimization results.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the ongoing support and assistance of the Wisconsin Department of Transportation and colleagues at the University of Wisconsin Traffic Operations & Safety Laboratory. Special thanks to Prof. Alan Horowitz of the University of Wisconsin-Milwaukee and to the developers of the original BALT tool, Mr. Ertan Ornek, and Dr. Do Nam.

REFERENCES

1 Hauer, E., E. Pagitsas, and B. T. Shin (1981). Estimation of Turning Flows from Automatic Counts, Transportation Research Record 795. Transportation Research Board, Washington, DC.

2 Lin, P & Rasp, J (1983). "A Short-Count Method for the Estimation of Traffic Turing Movements", Florida State University Department of Statistics, FSU Statistics Report M673, Tallahassee, FL .

3 Florida DOT (2012), "Project Traffic Forecasting Handbook", Chapter 6, pp. 6-98. Florida Department of Transportation, Tallahassee, FL.

4 Ren, J. & Rahman, A, (2009), "Automatically Balancing Intersection Volumes in a Highway Network." 12th TRB Transportation Planning Applications Conference, Transportation Research Board, Washington, DC.

5 Xin, W., Hourdos, J., and Michalpopoulos, P. (2006). "Streamlining the Traffic Modeling Process for Implementaion in the Twin Cities Freeway Network – Phase II Final Report". Minnesota Department of Transportation, St Paul MN.

6 Liao, C. and Davis, G. (2006). "Bus Signal Priority Based on GPS and Wireless Communications Phase I - Simulation Study". University of Minnesota Center for Transportation Studies, Minneapolis, MN .

7 Federal Highway Administration (2001), "Traffic Monitoring Guide," Section 3, pp 3-42 to 3-49. Washington, DC.

8 Zhao, M., Garrick, N., Achenie, L., and Paladagu, S.,(1997). "Data Reconciliation Based Traffic Count Analysis System". University of Connecticut Transportation Institute, Storrs, CT.

9 Kwon, J., Petty, K., Shieh, E., Kopelias, P., Papandreou, K. (2007). "An Automatic Method for Imputing and Balancing Link Traffic Counts" *TRB 87th Annual Meeting Compendium of Papers CD*, Transportation Research Board of the National Academies, Washington, DC, 2008.

10 Van Vliet, D (2013). "Saturn Software User's Manual (v11.2),"Chapter 15, pp 15-13. Epsom, Surrey, UK.

11 Highways Agency (1996), "Design Manual for Roads & Bridges," Volume 12, Section 2, Chapter 4.4.42, pp 4/28 "Traffic Appraisal of Roads Schemes: Traffic Appraisal Advice: Validation Acceptability Guidelines." British Crown copyright.

12 Transport for London (2010), "Traffic Modelling Guidelines Version 3.0" Appendix III, pp 179. London, UK.

13 Microsoft Corporation software support website, "Solver Uses Generalized Reduced Gradient Algorithm." http://support.microsoft.com/kb/82890 accessed 2013-07-13.

14 McGowen, P & Sanderson, M. (2011). "Accuracy of Pneumatic Road Tube Counters", Institute of Transportation Engineers Western District Annual Meeting, Institute of Transportation Engineers, Washington, DC.

15 Highways Agency (1991), Design Manual for Roads & Bridges, Volume 12, Section 1, Chapter 10.3, pp 10-7 "Traffic Appraisal Manual: Estimating the Accuracy of Ground Counts." British Crown copyright.